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AIR QUALITY AND RELATED IMPACTS
VOLUME I

DOCUMENTATION IN SUPPORT OF KEY ORBES AIR QUALITY FINDINGS

by

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16. ABSTRACT

This report was prepared as part of the Ohio River Basin Energy Study (ORBES), a multi-disciplinary research program supported by the Environmental Protection Agency. The extensive air quality analysis undertaken for the ORBES included examination of pollutant emissions and resulting concentrations under various policy assumptions; collection of additional particulate and sulfur oxide measurements from the utilities for use in the analysis of current conditions; evaluation of the meteorological conditions under which maximum pollutant concentrations are likely to occur; examination of the validity of using conventional dispersion models for predicting worst-case pollution conditions; and cataloguing meteorological conditions under which regional pollution episodes occur.

In this report, the focus is on the factual materials used to formulate the key air quality findings set forth in the main report of this study. It draws from Volumes II and III of the same series. Volume II is entitled "Air Quality and Meteorology in the Ohio River Basin: Baseline and Future Impacts;" Volume III, "Selected Impacts of Electric Utility Operations in the Ohio River Basin (1976-2000): An Application of the Utility Simulation Model."

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FOREWORD

The Ohio River Basin Energy Study (ORBES) is an interdisciplinary, multi-university inquiry into the environmental, economic and social impacts of energy facility development in a major portion of the Ohio River Basin. The study was initiated by the U.S. Environmental Protection Agency in 1976 in response to a directive from the U.S. Senate Appropriations Committee.

Most of the ORBES research was conducted by a group of faculty members at the University of Illinois, Indiana University, the University of Kentucky, the University of Louisville, The Ohio State University, the University of Pittsburgh, Purdue University, and West Virginia University. In a few instances, the necessary expertise was found at other universities or independent research organizations.

This report is one of a series produced in support of the overall ORBES assessment. For a summary of the entire study, see Ohio River Basin Energy Study (ORBES): Main Report (EPA-600/7-81-008), by the ORBES Core Team, and published by the U.S. Environmental Protection Agency.

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Chapter 1
INTRODUCTION

The air quality analysis undertaken in the ORBES project was quite extensive. The investigation not only examined the pollutant emissions and resulting concentrations under various policy assumptions, but also was responsible for (1) collecting additional particulate and sulfur oxide measurements from the utilities for use in the analysis of current conditions, (2) evaluating the meteorological conditions under which maximum pollutant concentrations are likely to occur, (3) examining the validity of using conventional dispersion models for predicting the worst case pollution conditions, and (4) cataloging the meteorological conditions under which regional pollution episodes occur.

This report, Volume I of the air quality series, will focus on the factual materials used to formulate the key findings in the main report. This volume will draw from the remaining volumes (Vols. II and III), which deal with important air quality issues examined in this study, as well as from support research.

The organization of this report parallels that of the main report. First, the materials in support of the findings under current conditions are examined. Then, the modeling results used to estimate the air impacts for various environmental policy options are discussed.

Chapter 2
CURRENT CONDITIONS

2.1 Ambient Concentrations

- In 1977, 11 of the 423 ORBES-region counties violated the national ambient air quality standards (NAAQS) for sulfur dioxide. An additional 13 counties did not have available the full, 24-hour prevention of significant deterioration (PSD) increment for sulfur dioxide to accommodate new sources since the ambient concentrations were at or just below the NAAQS. Most of the counties that violated the NAAQS were clustered on the Ohio-Pennsylvania-West Virginia border. However, since over 50 percent of the counties in the ORBES region are without sulfur dioxide monitoring, the number of 1977 violations probably is underestimated.

- Nearly 4 years (1974-77) of sulfur dioxide data from a utility monitoring network located primarily along the Ohio River main stem further indicate that about half the available annual air resource for sulfur dioxide (80 micrograms per cubic meter--NAAQS) has been used up around this network in the vicinity of the lower reaches of the Ohio River, and all or nearly all has been used up in the vicinity of the upper reaches. Data from a more regional monitoring network that were collected between August 1977 and October 1978 show that sulfur dioxide "annual averages" throughout the rest of the region ranged from one-fourth to one-third the annual standard.

- The nonattainment of standards for total suspended particulates (TSP) has been a problem in the ORBES region. Of the counties that had TSP monitoring in 1977 (about half of the 423 counties), 130 violated the NAAQS for this pollutant. These counties and an additional 5 counties had less than the full PSD increment available. Moreover, many of the counties that violated the primary 24-hour NAAQS for TSP were clustered in extreme southwestern Ohio, and, again, along the Ohio-Pennsylvania-West Virginia border.

The national ambient air quality standards (NAAQS) for particulate matter and sulfur dioxide (see table 2-1) include both primary (health) and

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Table 2-1. National Ambient Air Quality Standards

	Primary Standard ($\mu g/m^3$)	Secondary Standard ($\mu g/m^3$)
Particulate matter		
Annual geometric mean	75	60
24-hour*	260	150
Sulfur Dioxide		
Annual arithmetic mean	80	-
24-hour*	365	-
3-hour*	-	1,300

NOTE: Pennsylvania has set standards for another pollutant, sulfate. The standards are 30 $\mu g/m^3$ for a 24-hour average and 10 $\mu g/m^3$ for a 30-day average. Neither of these is to be exceeded more than once a year.

*Not to be exceeded more than once a year.

Table 2-2. Maximum Allowable SO_2 and TSP Increments ($\mu g/m^3$) Under the Rules for Prevention of Significant Deterioration

	Class I	Class II	Class III
Particulate matter			
Annual geometric mean	5	19	37
24-hour maximum	10	37	75
Sulfur Dioxide			
Annual arithmetic mean	2	20	40
24-hour maximum	5	91	182
3-hour maximum	25	512	700

secondary (welfare) standards as well as three averaging times, namely, 3-hour, 24-hour, and annual average. The standards for the shorter averaging times of 3-hours and 24-hours may be exceeded only once per year at a particular location, otherwise a violation of the standards has occurred. The only ORBES state, and the only state in the entire eastern U.S. for that matter, with a sulfate standard is Pennsylvania.

Existing sources of sulfur oxides and particulate matter are constrained to meet the NAAQS, while new sources also are constrained to meet even stricter standards, namely, the maximum allowable SO_2 and TSP increments under the rules for prevention of significant deterioration (PSD) (see table 2-2). The PSD increments have been set for 3 different types of areas depending upon the amount of growth to be allowed: (1) Class I--essentially no growth within and near these special areas (national parks, wilderness areas, etc.), (2) Class II--areas where the air quality deterioration accompanying moderate industrial growth would not be considered significant, and (3) Class III--areas where the air quality could support considerable industrial growth. Currently, most of the U.S. outside of the Class I areas has been designated as Class II with the exception of nonattainment areas. In all situations, the NAAQS still are controlling in that if the "baseline concentration" plus the increment is greater than the NAAQS, then the situation exists in which less than the full PSD increment is available to accommodate growth.

At American Electric Power (AEP) and/or National Aerometric Data Bank (NADB) monitors in 1977, the counties in the ORBES region with violations of the NAAQS for SO_2 were generally spread around the region except for the cluster of counties along the Ohio-Pennsylvania-West Virginia border (see figure 2-1).[1] However, even with the NADB and AEP data, a large number (over 50%) of the counties in the ORBES region still are without SO_2 monitoring. The best sources of additional SO_2 monitoring data are utility company monitors in the vicinity of their existing sources or proposed sites. A survey of the most recent data obtained from some of the utilities in the ORBES region, including AEP, has revealed the existence of elevated background concentrations outside the river valley, where most of the AEP monitors are located (Niemann, 1980), and a few nonattainment counties in addition to those in figure 2-1.

When the counties with SO_2 nonattainment are included, there are a substantial number of counties, especially in eastern Ohio, with less than the full Class II SO_2 PSD increment available at AEP and/or NADB monitors in 1977 (see figure 2-2). In fact, a summary of the counties that violated the NAAQS for SO_2 or had less than the full PSD increment available in 1977 (see table 2-3) is very substantial considering the number of counties without SO_2 monitoring. It is important to point out that the number of counties in these two categories is subject to change as the conventional data is more carefully scrutinized (some violations are invalidated for various reasons) and more of the special monitoring data is reviewed (more violations are found).

It is of interest to see the extent of SO_2 nonattainment in the AEP network during the nearly 4-year (1974-1977) period of data analyzed (Mills, 1979). (The locations of the AEP plants and their sulfur dioxide monitors in the Ohio River Basin are principally along the main stem of the river

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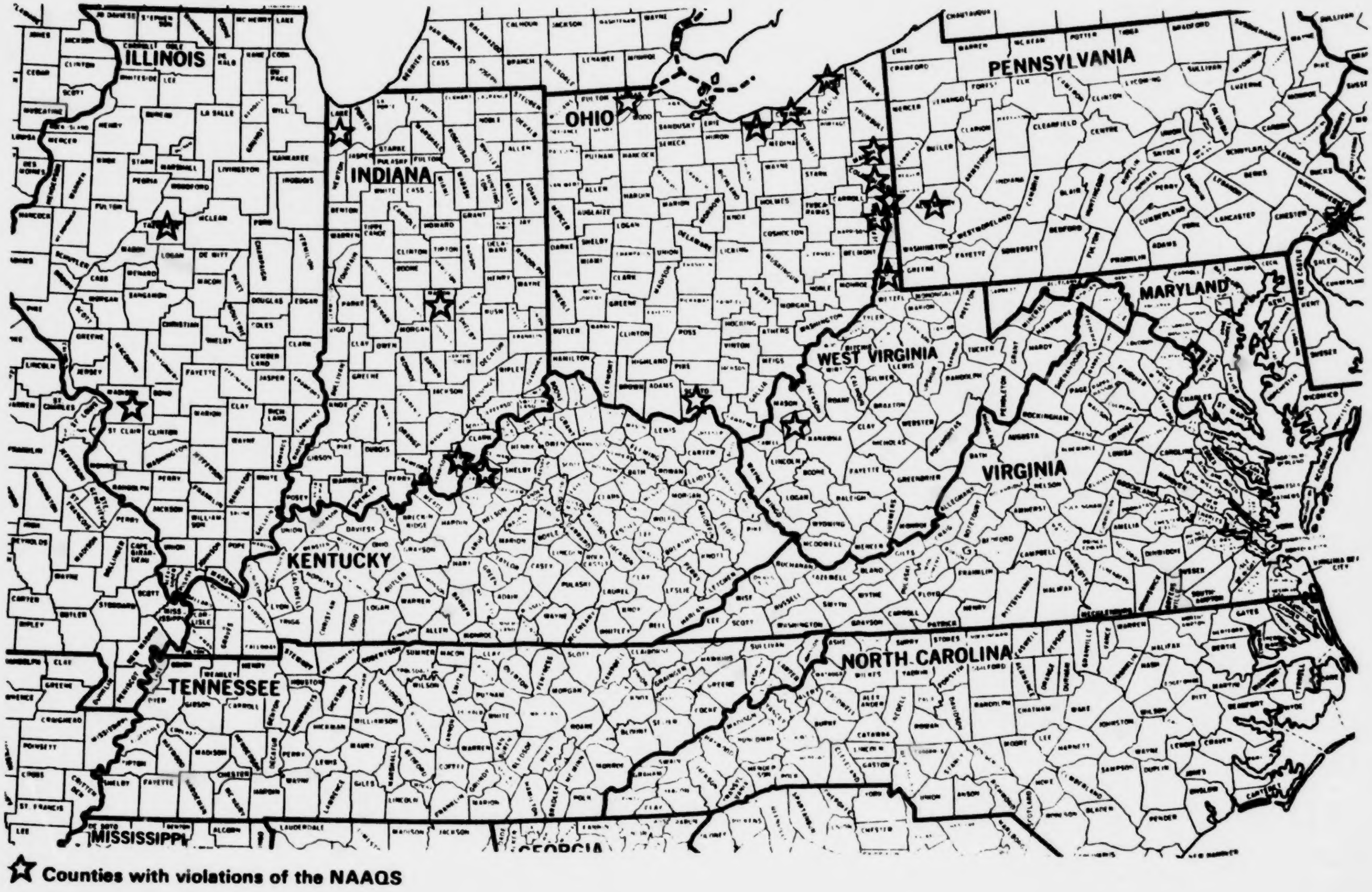
[1] The NADB is the EPA central data bank to which the local, county, and state air pollution agencies submit their monitoring data.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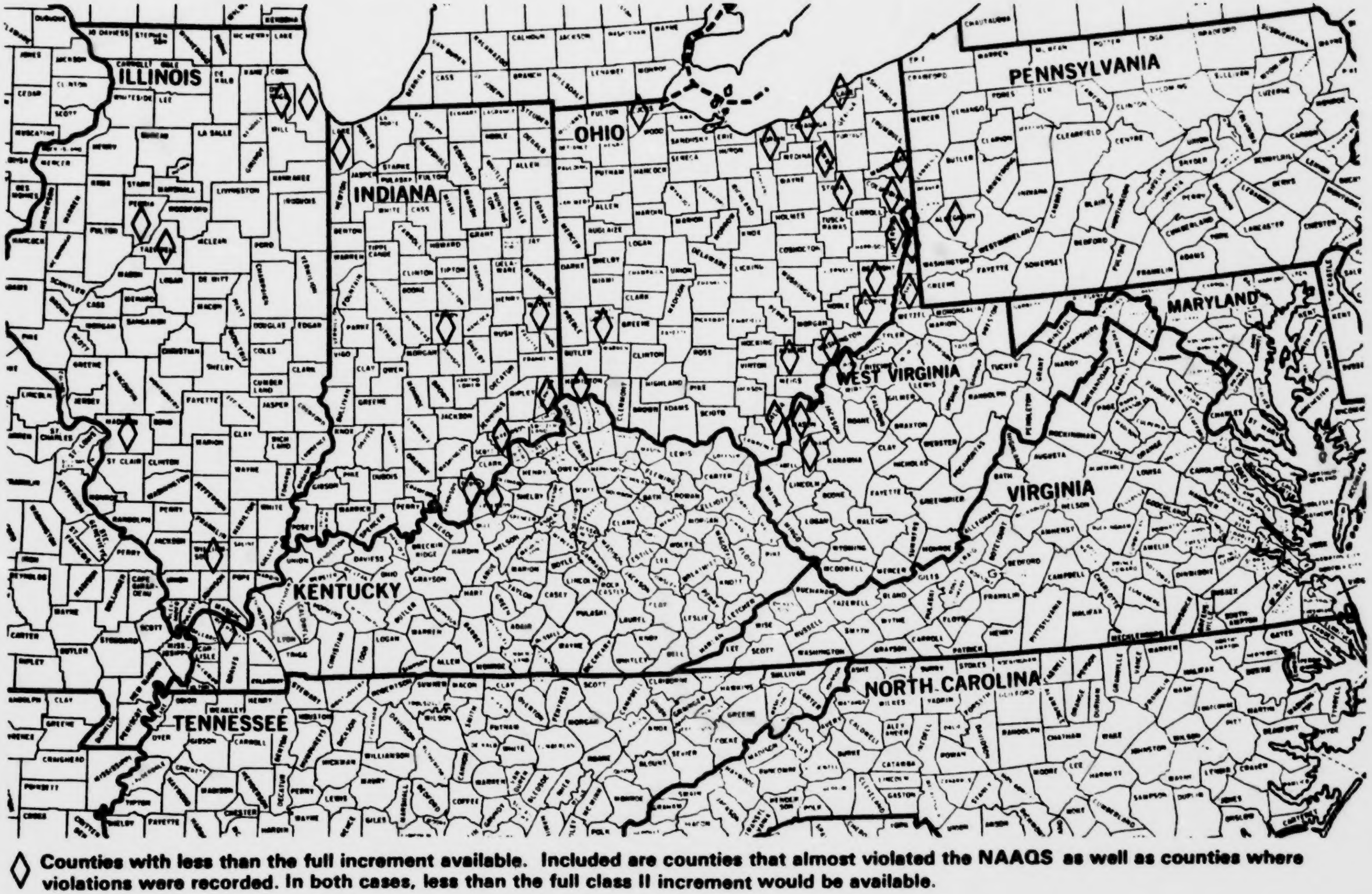
Counties with violations of the NAAQS

Figure 2-1. Counties with violations of the NAAQS for SO_2 at AEP and/or NADB monitors in 1977.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◇ **Counties with less than the full increment available. Included are counties that almost violated the NAAQS as well as counties where violations were recorded. In both cases, less than the full class II increment would be available.**

Figure 2-2. Counties with less than the full Class II SO_2 PSD increment available at AEP and/or NADB monitors in 1977.

Table 2-3. Number of ORBES Counties That Violated the NAAQS for SO_2 or TSP or Had Less Than the Full PSD Increment Available in 1977 (According to NADB Data)

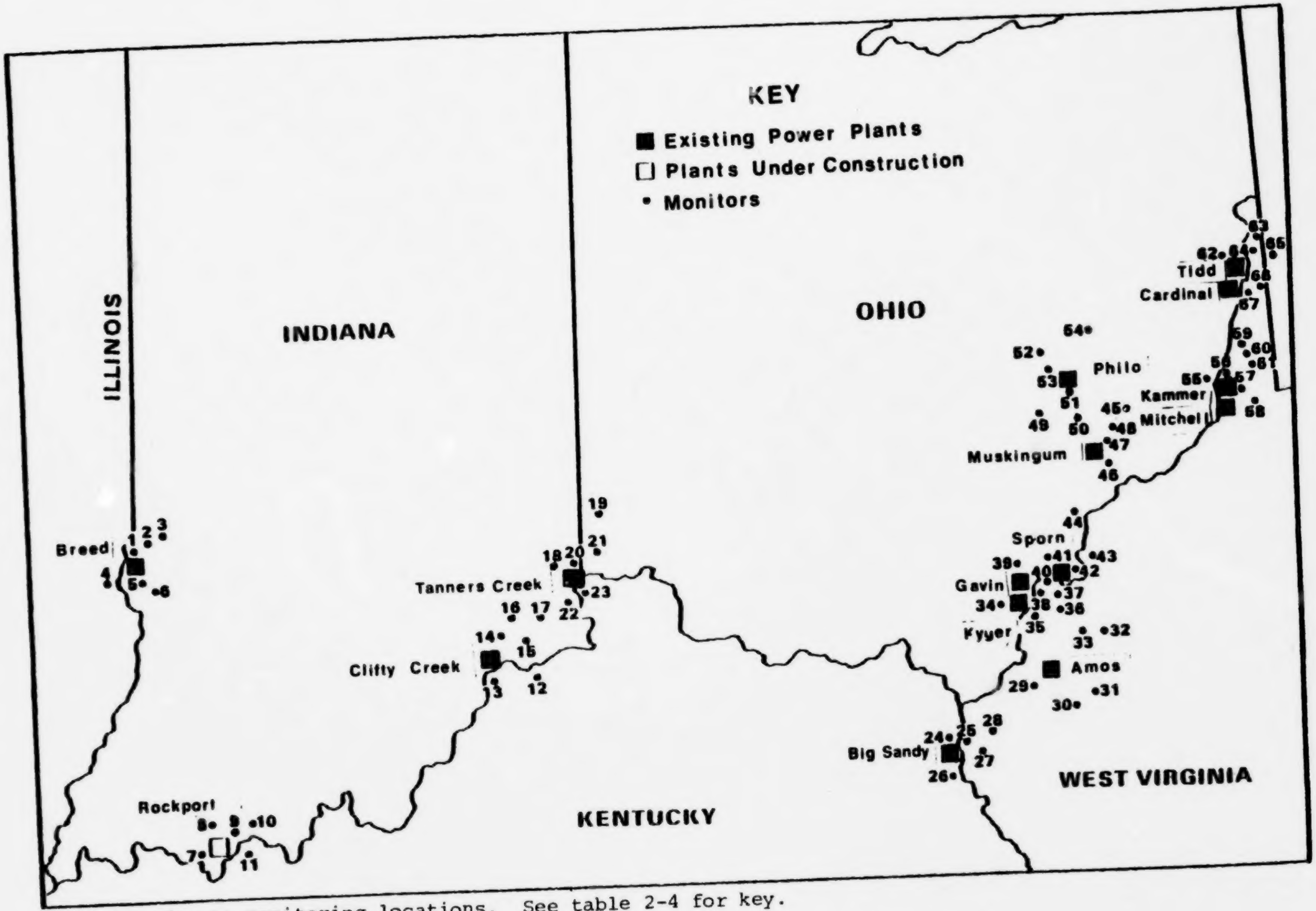
State	Violation of TSP NAAQS[a]	Less Than Full TSP PSD Increment Available[b]	Violation of SO_2 NAAQS[c]	Less Than Full SO_2 PSD Increment Available[d]	Total Counties in ORBES
Illinois	17	13	2	4	85
Indiana	11	16	2	4	83
Kentucky	39	49	1	2	120
Ohio	43	42	4	9	68
Pennsylvania	8	4	1	1	19
W. Virginia	12	11	1	4	48
TOTALS	130	135	11	24	423

[a] The violations are defined as two observations greater than 260 μg/m^3 (primary 24-hour), two observations greater than 150 μg/m^3 (secondary 24-hour), one observation equal to 75 μg/m^3 (primary annual), or one observation equal to 60 μg/m^3.

[b] A county with less than the full PSD increment available is defined as one with at least one monitor at which the measured concentration plus the Class II PSD increment equal a violation of the standards, e.g., $224+37>260$, $114+37>150$, $41+19=60$, and $56+19=75$. With one exception, a monitor with a measured violation is not eligible for consideration in this category. The exception is a monitor showing violation of the secondary 24-hour standard (> 150 μg/m^3) that leaves less than the full PSD increment toward the primary 24-hour standard, e.g., $224 \leq x \leq 260$.

[c] The violations are defined as two observations greater than 1300 μg/m^3 (3-hour), two observations greater than 265 μg/m^3 (24-hour), and one observation greater than or equal to 80 μg/m^3 (annual).

[d] A county with less than the full PSD increment available is defined as one with at least one monitor that does not by itself violate the NAAQS but would do so if the Class II PSD increment were added. A monitor with a measured violation is not eligible for consideration in this category.


KEY
■ Existing Power Plants
☐ Plants Under Construction
• Monitors
ILLINOIS
INDIANA
OHIO
KENTUCKY
WEST VIRGINIA
Breed
Rockport
Clifty Creek
Tanners Creek
Big Sandy
Amos
Kyger
Gavin
Sporn
Muskingum
Philo
Kammer
Mitchell
Cardinal
Tidd
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Numbers refer to monitoring locations. See table 2-4 for key.

Figure 2-3. Locations of American Electric Power (AEP) plants and sulfur dioxide monitors in the Ohio River Basin.

Table 2-4. American Electric Power Monitors

BREED	
1	Sludge Pit
2	Prairie Creek
3	Youngstown
4	York
5	Fairbanks
6	Turman Creek
ROCKPORT	
7	Rockport
8	Grandview
9	Newtonville
10	Evanston
11	Chestnut Grove
CLIFTY CREEK	
12	Canip Creek
13	Liberty Ridge
14	North Madison
15	Rykers Ridge
16	Hebron Church
17	Bacon Ridge
TANNERS CREEK	
18	Wilson Creek
19	Kilby Road
20	Lawrenceburg
21	Elizabethtown
22	Dutch Hollow
23	Petersburg
BIG SANDY	
24	Catalpa
25	Prichard
26	Five Forks
27	Wolf Creek
28	Toms Creek
AMOS	
29	Rockstep
30	Howard Fork
31	Guthrie
32	Fisher Ridge
33	Jeffers Ridge
GAVIN, KYGER, SPORN*	
34	Kerr
35	Henderson
36	Mount Alto
37	New Haven
38	Lakin
39	Wolfpen
40	Mason
41	Five Points
42	Dorcas
43	Neptune
44	Coolville
MUSKINGUM	
45	Caldwell
46	Beverly
47	Hackney
48	Rich Valley
PHILO	
49	Irish Ridge
50	Fox Run
51	Philo
52	Indian Run
53	Duncan Falls
54	Salt Creek
KAMMER-MITCHELL	
55	German Ridge
56	Grave Creek
57	Nixon Ridge
58	Bowman
59	McClain Run
60	Blairs Ridge
61	Lone Oak
CARDINAL-TIDD	
62	New Alexandria
63	Fowlerstown
64	Wellsburg
65	Meadowcroft
66	Bethany
67	Power

---

*Locations of Kyger and Sporn Plants are specified relative to the location of Gavin Plant.

Table 2-5. First and Second Highest Daily SO_2 Concentrations $\geq$ 365 $\mu g/m^3$ in the AEP Monitoring Data 1974-1977

Plant	Site No.*	Date	Highest $SO_2 (\mu g/m^3)$	Date	2nd Highest $SO_2 (\mu g/m^3)$
Amos	29	3/11/77	384	8/20/77	340
Cardinal-	62	10/11/74	490	8/20/74	408
Tidd	62	5/28/75	558	8/1/75	417
	64	2/14/75	439	1/21/75	317
Kammer-	57	10/3/75	492	2/14/75	284
Mitchell	56	1/1/77	429	1/10/77	241
	58	1/5/77	424	1/4/77	416
Tanners	20	4/18/75	534	1/24/75	491
Creek	20	11/25/76	529	11/26/76	376
	22	3/24/77	450	4/15/77	311

* See table 2-4 for key.

and secondarily along the major tributaries--see figure 2-3 and table 2-4). A tabulation of the first and second highest daily SO_2 concentrations greater than the 24-hour standard (see table 2-5) shows there were only 5 actual violations at only 3 of the 10 plant sites. One can, of course, argue that this small number of violations is probably a lower bound since the number of monitors around each plant is relatively small and the probability of the maximum impact occurring at these few monitor locations is low.

In terms of annual average SO_2 concentrations at the AEP sites during the same period, figure 2-4 shows that about half of the available air resource (80 $\mu g/m^3$) has been used up in the vicinity of the lower reaches of the Ohio River and all or nearly all has been used up in the vicinity of the upper reaches. Another major source of SO_2 background concentration measurements in the ORBES region is the Sulfate Regional Experiment (SURE) Phase II conducted between 1977 and 1978.[2] The SURE II station numbers and locations (see figure 2-5) and the key (see table 2-6) show that 22 of the 54 stations are in the 6 ORBES states. The "annual average" SO_2 concentrations from SURE II in the ORBES region (figure 2-6) show values ranging from about one-fourth to one-third of the annual standard (80 $\mu g/m^3$).

The counties with violations of the NAAQS for TSP or with less than the full PSD increment available in 1977 (see table 2-3) totaled 130 and 135, respectively, in the ORBES region. These numbers are significant in light of the total number of counties (423) in the ORBES region and the fact that only about one-half of the total counties had TSP monitoring in 1977.

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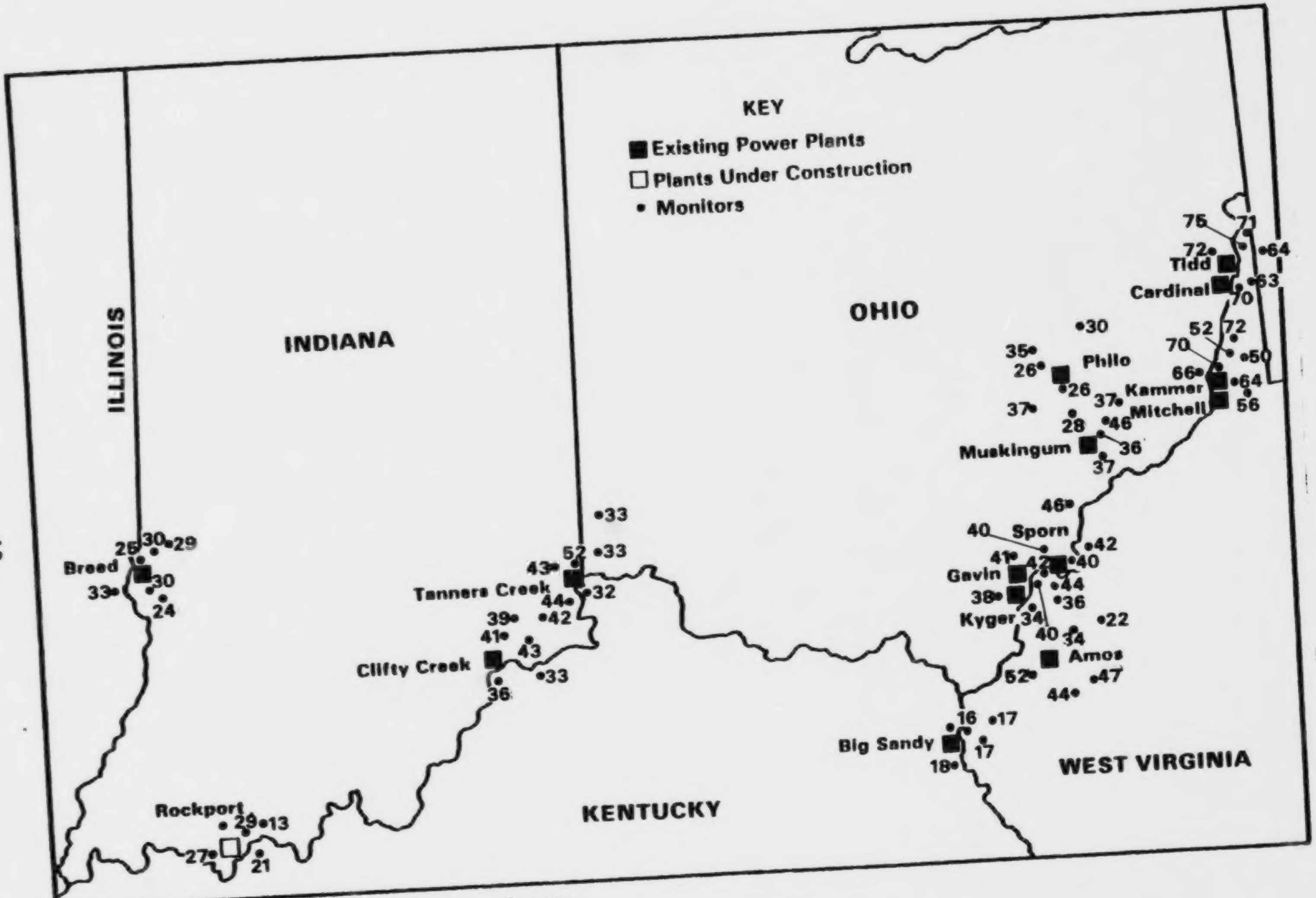
[2] The SURE II data base and results have been described recently by Mueller, et al (1979).


KEY
■ Existing Power Plants
□ Plants Under Construction
• Monitors
ILLINOIS
INDIANA
OHIO
KENTUCKY
WEST VIRGINIA
Breed
Rockport
Clifty Creek
Tanners Creek
Big Sandy
Amos
Kyger
Gavin
Sporn
Muskingum
Philo
Mitchell
Kammer
Cardinal
Tidd

*1974 and 1977 have less than a full year of data available.

Figure 2-4. Annual average SO_2 concentrations ($\mu g/m^3$) at American Electric Power monitoring sites, 1974-1977.

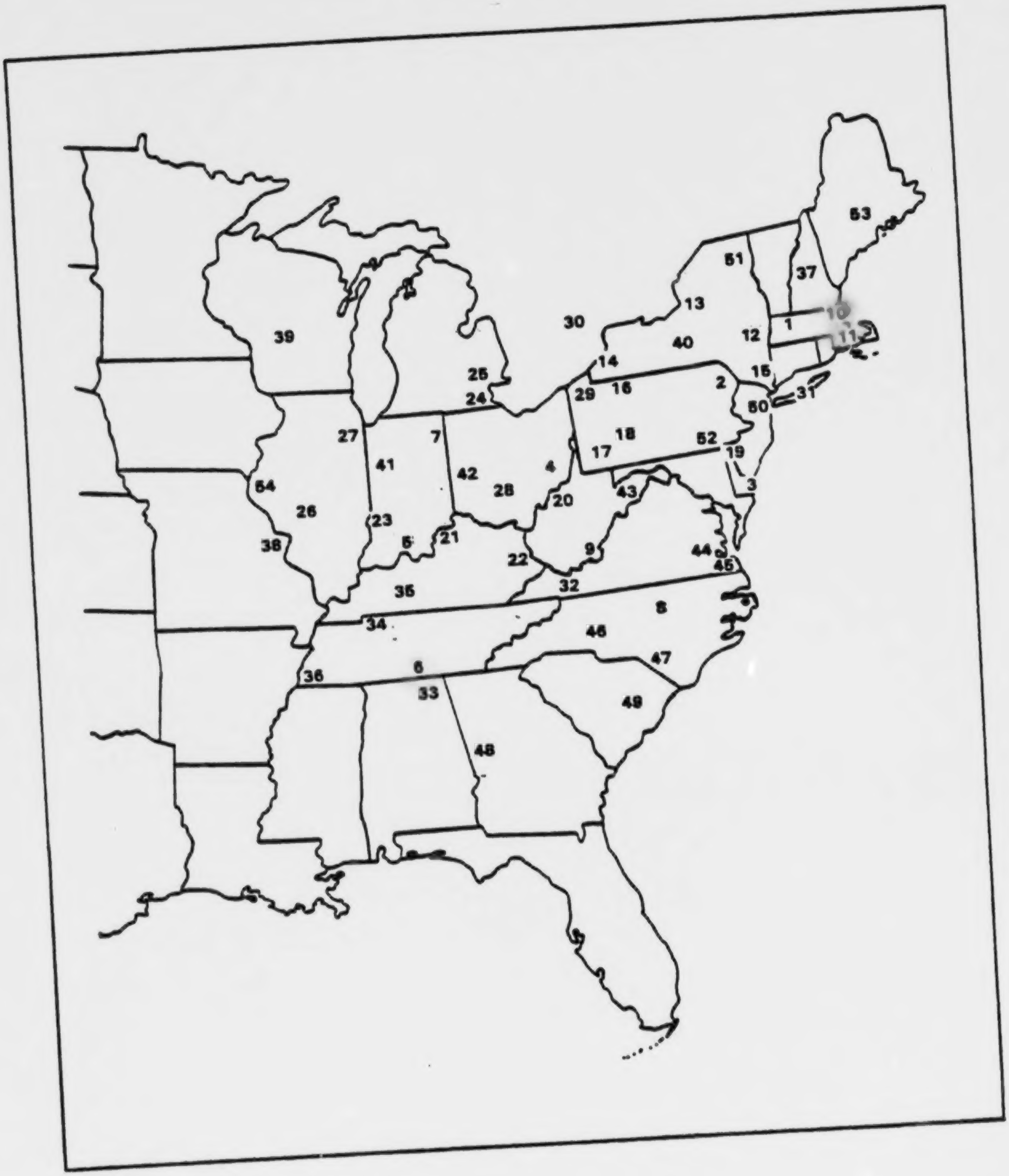

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Figure 2-5. SURE II station numbers and locations.

Table 2-6. Key to SURE II Station Numbers and Locations

	Station Name	City		Station Name	City
1	Montague	Amherst,MA	28*	Columbus	Columbus,OH
2	Scranton	Scranton,PA	29	Conneaut	Erie,PA
3	Indian River	Millsboro,DE	30	Toronto	Toronto,Ont.
4*	Philo	Zanesville,OH	31	Huntington	New York,NY
5*	Rockport	Owensboro,KY	32	Loves Mill	Bristol,TN
6	Giles City	Huntsville,AL	33	Hytop	Chattanooga,TN
7	Ft. Wayne	Ft. Wayne,IN	34	L-B-L	Nashville,TN
8	Chapel Hill	Raleigh,NC	35*	Paradise	Madisonville,KY
9*	Lewisburg	Lewisburg,WV	36	Memphis	Memphis,TN
10	Beverly	Boston,MA	37	Hanover	Hanover,NH
11	Fall River	Boston,MA	38	St. Louis	St. Louis,MO
12	Albany	Albany,NY	39	Nekoosa	Madison,WI
13	Oswego	Oswego,NY	40	Ithaca	Ithaca,NY
14	Dunkirk	Buffalo,NY	41*	Lafayette	Lafayette,IN
15	Roseton	Poughkeepsie,NY	42*	Dayton	Dayton,OH
16	Warren	Erie,PA	43*	Mt. Storm	Morgantown,WV
17*	Lewisville	Johnstown,PA	44	Chesterfield	Richmond,VA
18*	Brush Valley	Johnstown,PA	45	Yorktown	Newport News,VA
19	Wilmington	Wilmington,DE	46	Marshall	Charlotte,NC
20*	Parkersburg	Parkersburg,WV	47	Weatherspoon	Lumberton,NC
21*	Madison	Louisville,KY	48	Atlanta	Atlanta,GA
22*	Louisa	Ashland,KY	49	Columbia	Columbia,SC
23*	Sullivan	Terre Haute,IN	50	Chester	New York,NY
24	Detroit	Detroit,MI	51	Whiteface Mtn.	Plattsburg,NY
25	Port Huron	Detroit,MI	52	York	York,PA
26*	Springfield	Springfield,IL	53	Kents Hill	Augusta,ME
27	Braidwood	Joliet,IL	54*	Meredosia	Jacksonville,IL

*Stations in the ORBES region

It should be noted that, as in the case of SO_2, the number of counties with violations of the NAAQS for TSP or less than the full PSD increment available in 1977, is subject to some uncertainty. In the case of violations of the TSP secondary NAAQS, the actual number of counties with violations is likely to be larger than the number shown (table 2-3), which is based on just conventional EPA data since the AEP data and other special data sources show numerous violations (Niemann, 1980).

The 60 counties with violations of the primary 24-hour NAAQS for TSP in 1977 in the ORBES region (see figure 2-7) are clustered in extreme southwestern Ohio and along the Ohio-Pennsylvania-West Virginia border. The counties with violations of the secondary 24-hour NAAQS for TSP in 1977 in the ORBES region include all those counties with violations of the primary standard and those that violate the secondary standard. The frequency of nonattainment of the 24-hour TSP secondary standard in rural areas will be discussed later.

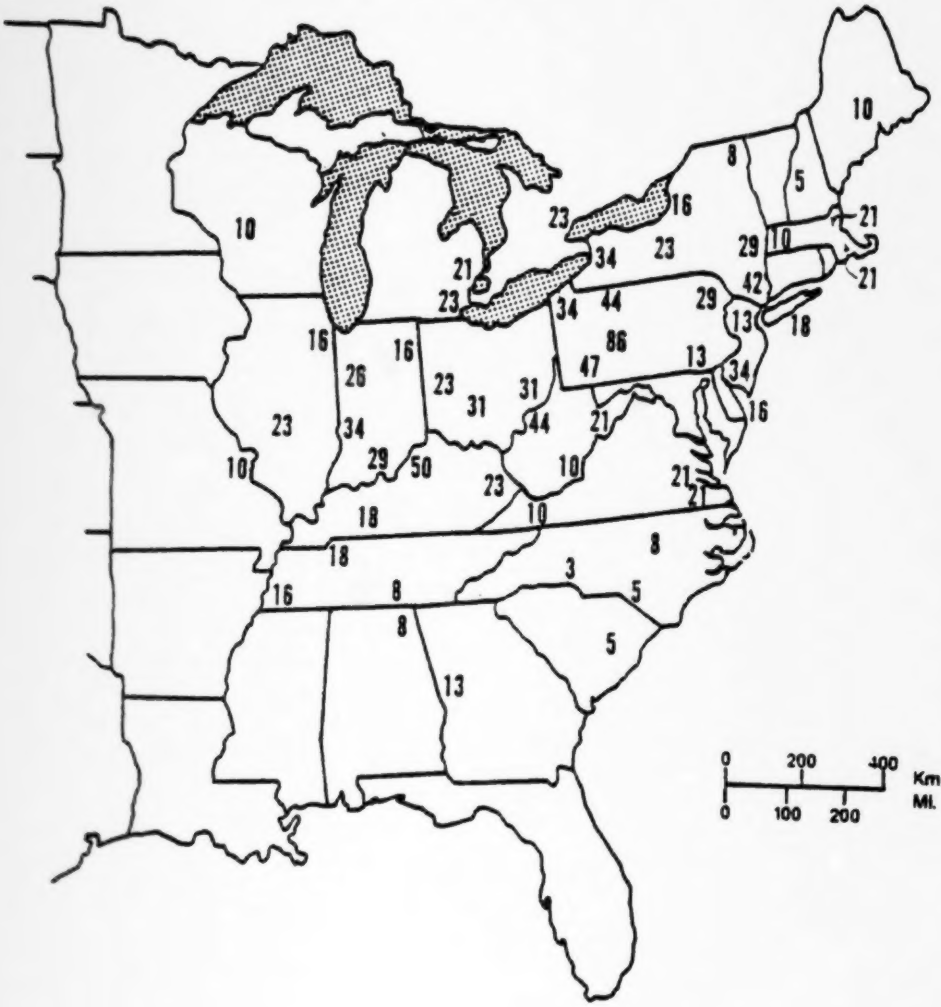
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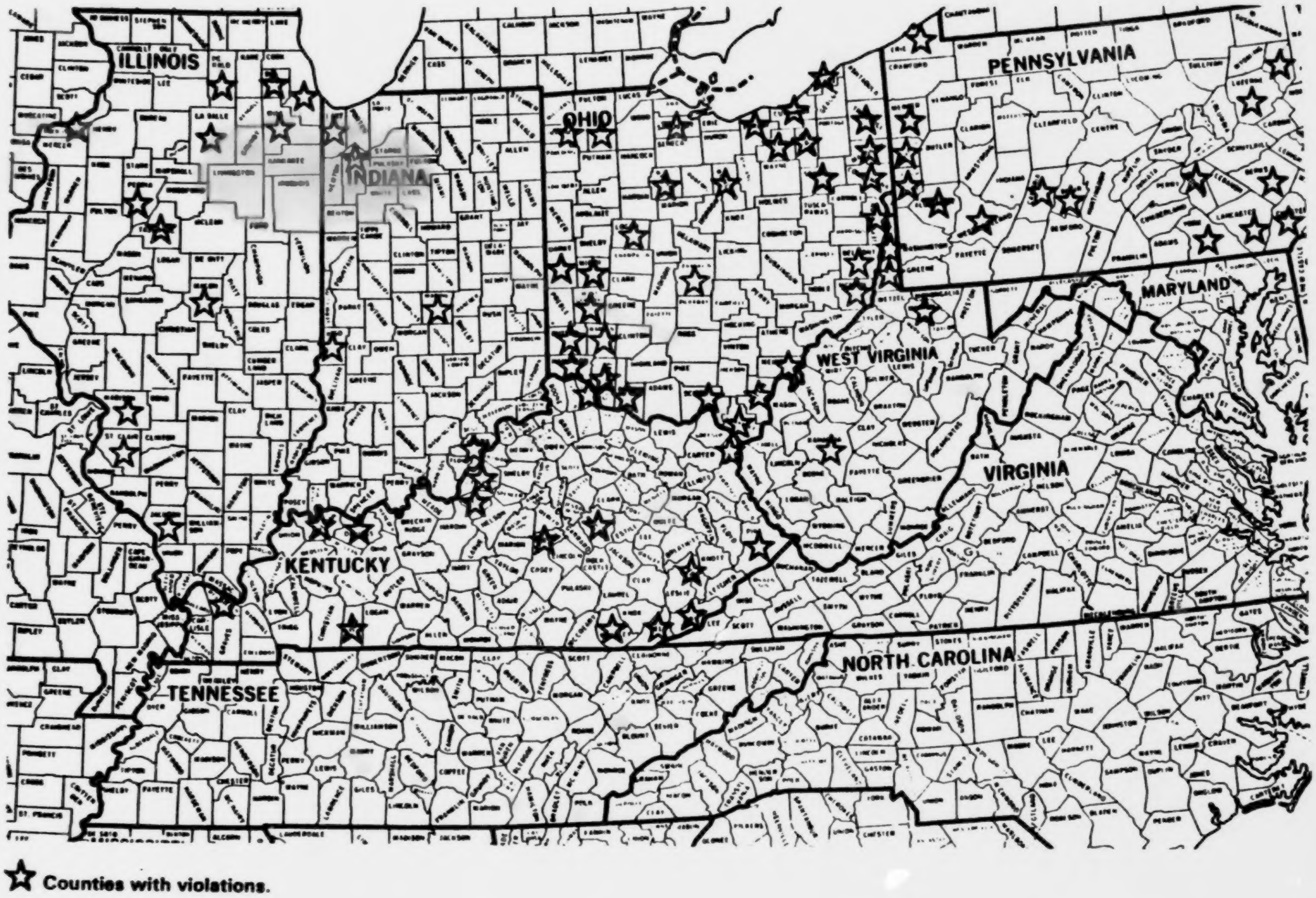
Figure 2-6. "Annual average" SO_2 concentrations ($\mu g/m^3$) from SURE II (August 1977 - October 1978).

2.2 Sulfur Oxide and Particulate Emissions

- In 1975 the ORBES states--Illinois, Indiana, Kentucky, Ohio, Pennsylvania, and West Virginia--were 6 of 10 contiguous states east of the Mississippi River with sulfur dioxide emissions greater than 1 million tons per year (there are 31 states in this area).



ILLINOIS
INDIANA
OHIO
PENNSYLVANIA
MARYLAND
WEST VIRGINIA
VIRGINIA
KENTUCKY
TENNESSEE
NORTH CAROLINA
☆ Counties with violations.

Figure 2-7. Counties with violations of the primary 24-hour NAAQS for TSP in 1977.

- In 1973, sulfur dioxide emissions from coal-fired electrical generating units in the ORBES region were at least 2.4 times the sulfur dioxide emissions from nonutility sources. Also in 1973, 15 air quality control regions (AQCRs) in the ORBES region (or almost 40 percent of the AQCRs completely or partially in the region) had sulfur dioxide emission densities greater than 10,000 kilograms per square kilometer. In 9 of these AQCRs, utility sources predominated, accounting for 50 percent or more of the total emissions and having emissions 10 or more times those of nonutility sources.

The ORBES region is an area of very high sulfur dioxide emission density. In fact, there appear to be subregional sulfur dioxide "emission corridors" in the region--in particular, subregions between Paducah, Kentucky; and Rockport, Indiana; Evansville and Terre Haute, Indiana; Louisville, Kentucky and Cincinnati, Ohio; and Huntington and Wheeling, West Virginia (see figure 2-8).

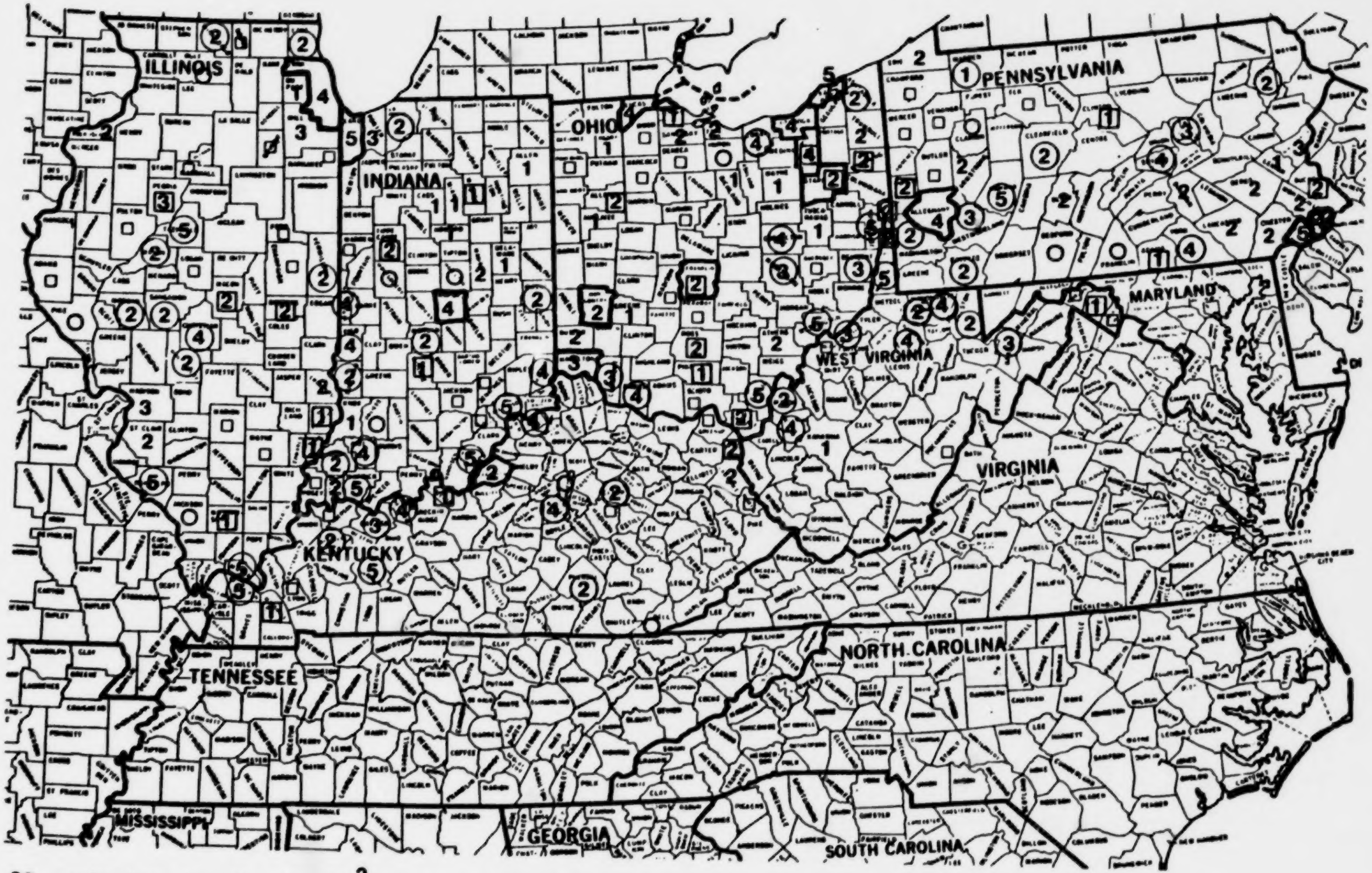
The total SO_x emissions and the ratio of utility to nonutility emissions by state for all the states east of the Mississippi River (see figure 2-9) show that SO_x emissions are greater than 10^6 tons/year in 10 of the 31 states (6 of which are the ORBES states) and that utility emissions are generally 2.4 times nonutility emissions or greater in these 10 states. In addition, these 10 states with very high SO_x emissions are all contiguous to one another, stretching from Missouri to New York and from Alabama to Michigan.

On a subregional scale, the AQCRs with high sulfur oxide emission densities, where fossil steam plants do or do not predominate as the major emission source (see figure 2-10) show a preference for the 11 states with high SO_x emissions density in which power plants are the predominant source and the other 2 AQCRs in this category are just south of the ORBES states in Tennessee and Alabama.

2.3 Sulfur Dioxide

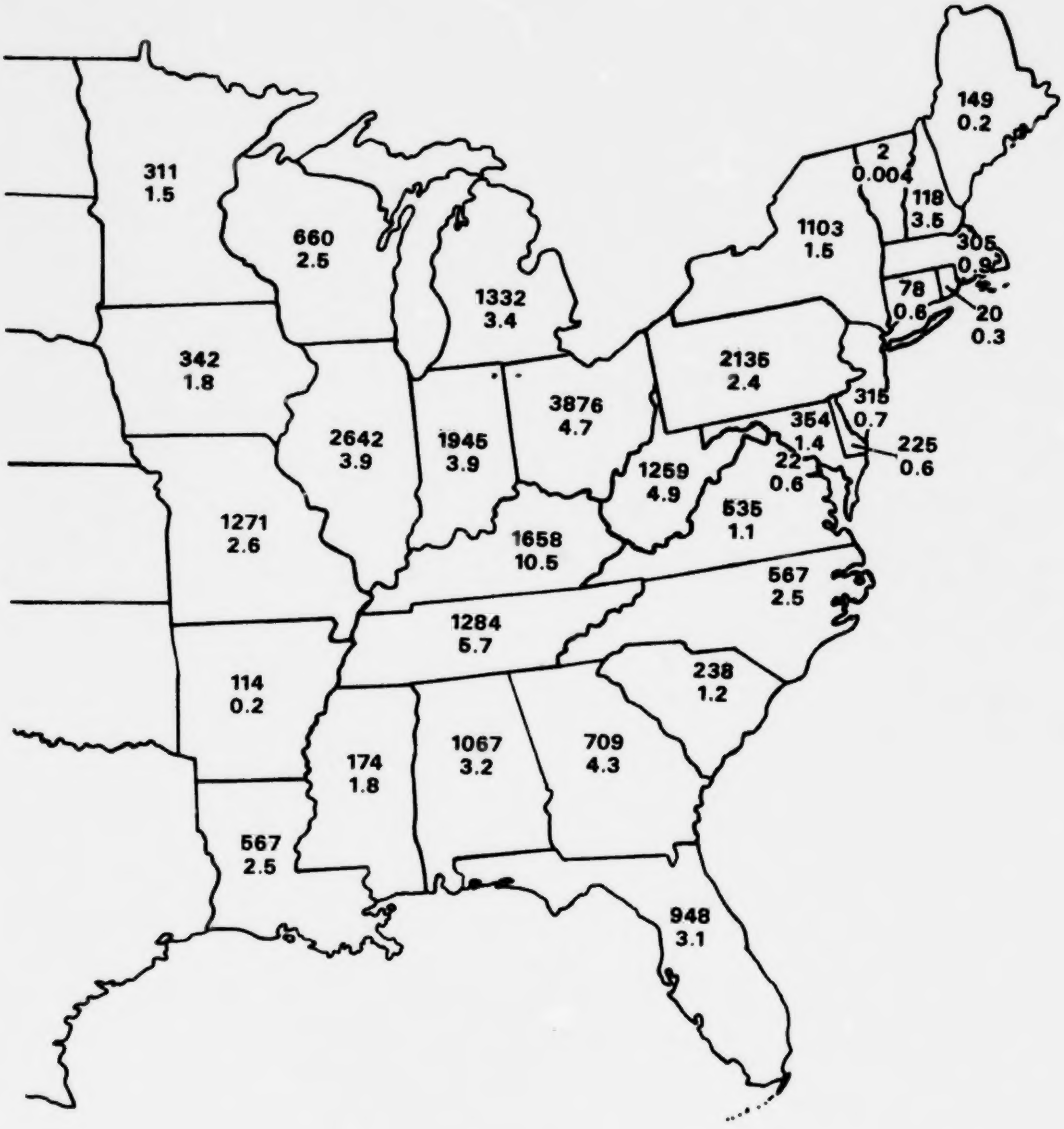
Electrical generating facilities in the ORBES region thus provide a majority of total regional sulfur dioxide emissions as well as a significant percentage of national emissions. For example, in 1976, ORBES-region coal-fired electrical generating units produced about 78 percent of the regional sulfur dioxide emissions from all sources. In terms of national emissions in that year, utility sulfur dioxide emissions in the region constituted nearly 52 percent of U.S. electric utility sulfur dioxide emissions and 32 percent of U.S. sulfur dioxide emissions from all sources.

Regional particulate emissions from electrical generating facilities, on the other hand, account for a small percentage of both regional and national emissions. In the same year, ORBES-region coal-fired electrical generating units produced about 22 percent of the regional particulate emissions from all sources, about 50 percent of the total U.S. electric utility


ILLINOIS
INDIANA
OHIO
PENNSYLVANIA
MARYLAND
WEST VIRGINIA
VIRGINIA
KENTUCKY
TENNESSEE
NORTH CAROLINA
MISSISSIPPI
GEORGIA
SOUTH CAROLINA

SO_x emission density (kg/km^2): 5 ->199,999; 4 - 100,000 - 199,999; 3- 50,000 - 99,999; 2 - 10,000 - 49,999; 1 - 5,000 - 9,999; blank - < 5,000. Predominant SO_x source: ○- fossil steam plants; □ - industrial plants. Heavily outlined counties have an area source emission density ≥ 10,000.

Figure 2-8. County sulfur oxide (SO_x) emissions densities and predominant source categories (NEDS, 1973).


149
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354
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535
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1271
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1658
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567
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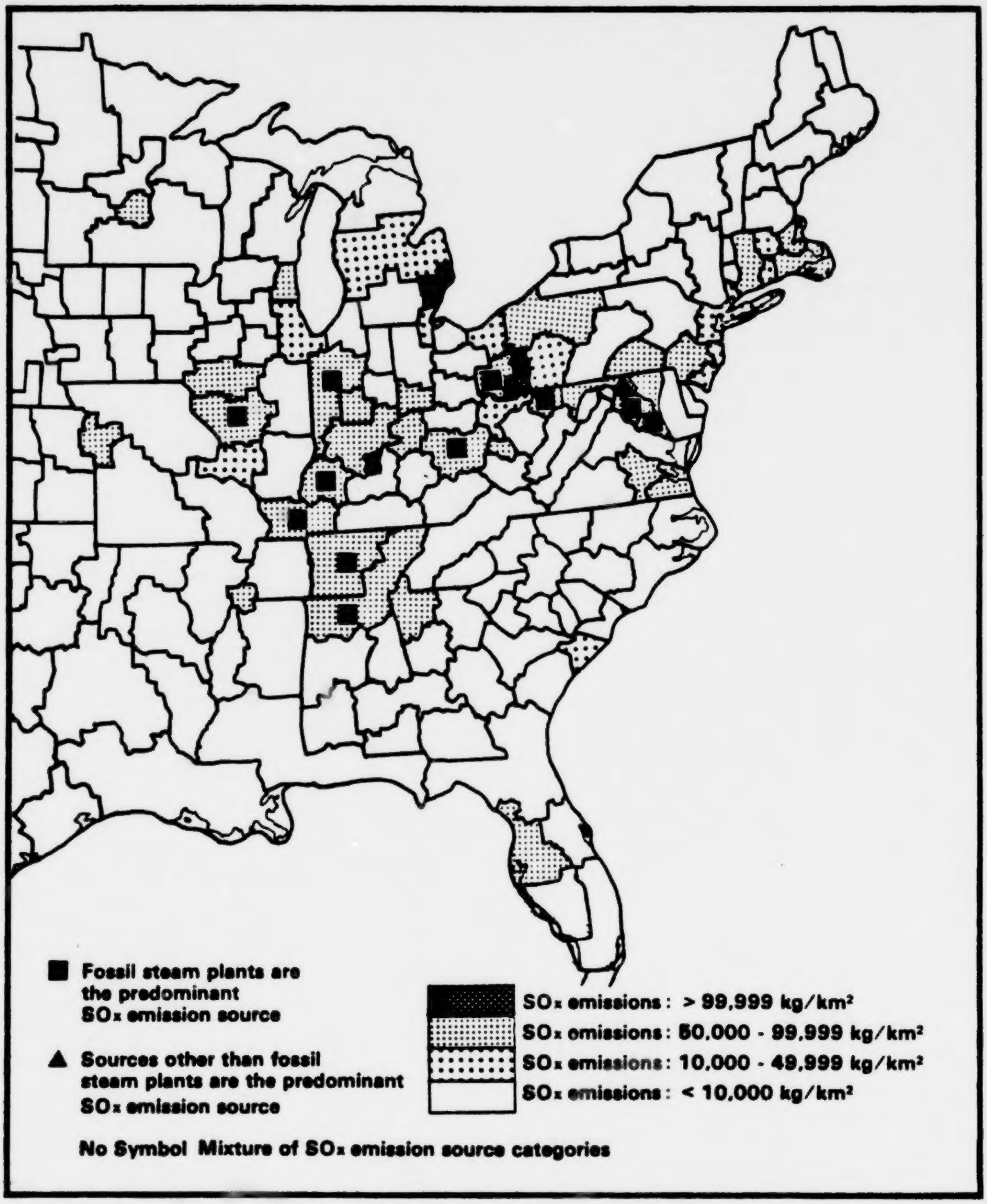
1284
5.7
238
1.2
114
0.2
1067
3.2
709
4.3
174
1.8
567
2.5
948
3.1

Figure 2-9. Total SO_x emissions (x 10^3 tons/year) and ratio of utility to nonutility emissions by state from EPA/NEDS 1975.

particulate emissions, and about 7 percent of total national particulate emissions from all sources (these calculations do not include "fugitive dust" contributions from unpaved roads and air strips).


■ Fossil steam plants are the predominant SOx emission source
▲ Sources other than fossil steam plants are the predominant SOx emission source
No Symbol Mixture of SOx emission source categories
SOx emissions : > 99,999 kg/km²
SOx emissions : 50,000 - 99,999 kg/km²
SOx emissions : 10,000 - 49,999 kg/km²
SOx emissions : < 10,000 kg/km²

Source: Data obtained from EPA National Emissions Data System, 1973.

Figure 2-10. AQCRs with high sulfur oxide emission densities, eastern United States.

2.3.1 Contribution of Long Range Transport to Local Concentrations

However, high sulfur dioxide emission densities within any subregion of the ORBES region may not be solely responsible for high sulfur dioxide concentrations in that subregion. Moreover, a location without high sulfur dioxide emissions still can experience high concentrations of this pollutant due to sources upwind. The explanation involves the transport of sulfur dioxide emissions--that is, the transport over regional-scale distances on the order of several hundred kilometers.

- Transport of emissions by extremely persistent winds (winds that blow from one direction for extended periods of time) is an important factor in subregional and regional sulfur dioxide concentrations. At several locations throughout the region, between 30 and 50 percent of the 25 highest daily sulfur dioxide concentrations each year are associated with transport by extremely persistent winds.

One of the most clear cut examples of the transport contribution to elevated SO_2 levels in the lower basin occurred during January 23-24, 1975. The hourly SO_2 and meteorological data for 23-24 January 1975 (see table 2-7) show that the winds on January 23 turned nearly 180 degrees--from a northerly, to a westerly, to a southwesterly, and finally to a south-southwesterly direction--from which they persisted in blowing directly toward the Lawrenceburg site for almost 24 hours. The elevated SO_2 concentrations at the Rockport monitors are especially significant since there is not a major emission source at that site and the nearest major sources south of the site are the Tennessee Valley Authority (TVA) plants over 50 km away.

The January 23-24, 1975, case becomes even more interesting when one examines the 25 highest SO_2 concentrations in the vicinity of the AEP-Clifty Creek Plant in 1975 (see table 2-8) and finds the concentrations on January 24 to be the highest and on January 23 to be the 4th highest for the entire year. In addition, a significant number of the 25 highest daily SO_2 concentrations are associated with extremely persistent winds, which are very indicative of transport from a particular direction for an extended period of time.

The distribution of the 25 highest daily SO_2 concentrations in the vicinity of the AEP Clifty Creek plant (see table 2-9) shows that the monitor with the largest number of the 25 highest concentrations can change from year to year and that about one-third to one-half of the 25 highest concentrations are associated with extremely persistent winds. This latter result generally holds true when the available results are summarized both within and outside the ORBES region (see table 2-10) and when different sector widths are used for computing extremely persistent winds. Since the majority of the monitors in all these networks measure primarily "background concentrations," the above results suggest that transport does make a significant contribution, in terms of magnitude and frequency, to elevated SO_2 concentrations upwind, within, and downwind of the ORBES region.

Table 2-7. *Hourly SO_2 and Meteorological Data for 23-24 January 1975*

Site	Parameter	Date	Hour																							
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
TANNERS CREEK PLANT																										
Lawrenceburg	SO_2[a]	1/23	24	107	79	42	13	47	144	228	362	443	335	356	105	55	181	351	613	563	490	351	385	605	631	451
		1/24	199	118	286	189	493	629	710	639	741	642	576	796	642	545	660	459	503	713	267	220	432	375	453	487
Dutch Hollow	WS[b]	1/23	4.0	2.2	2.7	2.2	2.2	2.7	1.8	2.2	3.6	2.7	4.5	2.7	3.1	2.7	3.1	4.5	4.0	4.9	5.8	6.3	5.4	4.0	4.0	4.0
		1/24	3.6	3.1	3.6	3.6	4.0	4.0	4.5	4.9	4.5	4.0	3.1	4.5	4.9	4.5	4.9	4.9	4.9	4.9	6.3	6.7	7.6	6.3	7.2	7.6
Dutch Hollow	WD[c]	1/23	342	312	300	266	277	244	219	219	218	238	225	225	220	221	214	208	202	201	203	205	214	220	212	206
		1/24	220	219	214	212	212	208	210	199	207	211	202	195	201	201	199	204	201	193	191	182	189	198	205	208
Dutch Hollow	TD[d]	1/23	-4	-2	-7	-10	-11	-11	-11	-11	-11	-12	-14	-16	-14	-16	-14	-14	-12	-6	-2	-6	-6	-3	-1	-3
		1/24	-8	-6	0	-3	-7	2	3	1	0	-6	-13	-13	-13	-13	-12	-11	-7	-3	1	0	-3	-2	-4	-6
ROCKPORT SITE																										
Newtonville	SO_2[a]	1/23	10	8	5	5	8	5	24	115	131	89	60	58	83	186	107	162	141	181	299	220	144	275	398	254
		1/24	126	113	121	123	118	105	105	79	79	73	71	60	47	34	26	45	100	149	86	71	60	50	58	97
Rockport	SO_2[a]	1/23	16	10	8	8	5	3	13	325	291	107	66	63	47	60	73	73	165	178	314	257	176	176	149	134
		1/24	178	131	60	55	63	102	86	115	107	79	89	73	55	89	76	39	42	81	68	63	68	86	94	110
Grandview	WS[b]	1/23	2.7	1.3	1.3	1.3	1.3	1.8	1.3	1.3	2.2	-	-	-	-	1.3	2.2	3.1	4.5	4.5	4.9	4.0	4.5	4.0	4.9	4.5
		1/24	3.1	3.6	3.1	3.6	3.1	3.6	3.6	3.6	3.6	3.6	3.6	4.5	4.0	3.6	4.5	4.0	4.5	5.8	5.4	6.3	7.2	6.3	7.2	6.7
Grandview	WD[c]	1/23	342	323	359	24	Calm	170	180	178	182	167	182	197	222	203	187	178	182	184	185	189	177	177	177	190
		1/24	203	195	197	195	184	177	176	176	170	171	181	187	184	185	198	207	203	191	181	184	190	187	191	193
Grandview	TD[d]	1/23	-13	-13	-12	-12	-12	-12	-12	-11	-11	-10	-10	-10	-10	-11	-16	-20	-20	-14	-12	-12	-11	-10	-10	-10
		1/24	-11	-11	-10	-11	-10	-10	-10	-10	-10	-11	-17	-19	-13	-13	-13	-12	-9	-3	-2	-2	-3	-4	-6	-7
CLIFTY CREEK PLANT																										
Hebron Church	SO_2[a]	1/23	21	18	18	21	21	21	34	50	89	63	92	225	194	45	50	461	521	238	278	411	508	134	191	204
		1/24	202	152	128	165	152	225	246	338	238	367	393	162	369	233	37	63	37	18	34	34	29	66	81	207
North Madison	SO_2[a]	1/23	24	24	24	26	26	24	24	26	29	26	26	68	71	55	89	430	684	844	867	631	123	68	388	739
		1/24	422	236	314	275	309	257	212	212	134	252	341	655	1779	671	131	215	84	39	66	81	45	445	228	50
Liberty Ridge	WS[b]	1/23	4.0	2.2	1.3	0.9	0.4	1.8	1.3	1.8	2.7	3.1	1.8	1.8	2.7	2.2	3.1	3.6	4.5	4.0	4.5	4.5	4.9	4.0	4.0	3.6
		1/24	3.6	3.1	3.6	2.7	3.1	3.6	3.6	4.5	4.5	4.9	4.0	4.9	4.0	4.5	4.9	4.5	4.0	4.5	5.8	6.7	6.7	7.2	7.2	7.6
Liberty Ridge	WD[c]	1/23	338	315	312	Calm	Calm	213	210	218	209	201	211	213	202	220	217	199	194	196	193	193	199	191	187	188
		1/24	214	208	195	195	190	192	189	191	187	185	184	175	188	190	188	193	180	176	177	178	182	189	192	194
Liberty Ridge	TD[d]	1/23	-11	-11	-12	-12	-11	-12	-11	-11	-11	-12	-12	-12	-14	-14	-13	-13	-13	-9	-7	-10	-8	-6	-8	-2
		1/24	-7	-10	-10	-10	-10	-9	-9	-8	-6	-9	-16	-19	-17	-14	-14	-12	-9	-2	-2	-2	-6	-7	-8	-7

[a] μg/m^3

[b] Wind Speed (m/s)

[c] Wind Direction (degrees from north)

[d] Temperature Difference (°Cx10^{-1}/100m)

Table 2-8. *25 Highest Daily SO_2 Concentrations in the Vicinity of the AEP Clifty Creek Plant and the Associated Meteorological Conditions, 1974-1977*

1974		1975		1976		1977	
Date/Site	Concentration µg/m^3	Date/Site	Concentration µg/m^3	Date/Site	Concentration µg/m^3	Date/Site	Concentration µg/m^3
10-4/14	278*	1-24/14	309*	11-25/16	212*	9-13/16	302*
9-11/14	225	10-21/17	252*	10-12/17	198*	4-27/15	214
12-4/14	224	10-22/17	250*	11-17/15	188	3-28/14	192
3-7/17	209	1-23/14	221*	2-24/17	186*	6-13/13	189
3-8/17	203	2-25/15	189	1-23/17	178*	1-6/14	189
10-8/14	197	11-2/17	183	5-9/15	177	8-30/15	172
11-23/14	188*	11-15/17	172*	12-22/16	169*	1-1/12	171*
10-27/16	188	4-23/14	166*	12-15/17	167*	1-9/14	171
10-3/14	182	12-19/17	161	12-14/17	166*	5-27/14	170
10-9/14	157	2-8/15	158*	2-27/17	166	10-8/16	165*
8-12/15	156	10-7/17	155	11-2/17	165*	1-2/15	164
11-22/14	147	3-4/12	155*	5-5/16	163*	6-3/13	163
8-23/15	143*	11-1/17	155	11-6/17	158*	1-5/14	158*
12-28/15	142	4-1/17	151*	12-27/16	158*	10-21/16	156*
10-30/14	140*	12-11/17	146*	10-28/13	155	2-10/17	155*
11-9/14	138	3-11/13	145	4-22/15	152*	3-8/17	154
7-9/14	137	4-28/17	141*	7-21/17	147	9-17/17	153*
10-5/16	136*	12-7/13	139*	11-16/12	146	1-26/17	152*
11-17/15	133	3-5/16	136	8-3/13	145*	8-9/17	152
10-23/15	131*	1-21/14	135	8-24/12	140*	3-31/12	151
7-4/14	128*	6-4/16	132*	11-14/15	139	1-11/15	150*
12-10/14	123*	1-11/15	131*	3-18/17	138	2-9/17	150
11-8/14	122	11-18/17	131*	3-22/15	137	9-8/16	147*
10-22/15	122	5-21/17	131	9-27/14	137*	4-3/13	146
3-9/15	120	2-20/17	127	6-30/12	133*	4-28/17	144

*Extremely persistent winds for 7 or more consecutive hours within an 11.25° sector on the day indicated

Note: For Key to site numbers, see Table 2-4.

Table 2-9. Distribution of 25 Highest Daily SO_2 Concentrations in the Vicinity of the AEP Clifty Creek Plant and the Associated Meteorological Conditions, 1974-1977

Location[+]	Name	1974	1975	1976	1977
17	Bacon Ridge	2(0)*	13(7)	10(7)	7(3)
15	Rykers Ridge	7(2)	3(2)	5(1)	4(1)
14	North Madison	14(5)	4(3)	1(1)	5(1)
16	Hebron Church	2(1)	2(1)	4(4)	4(4)
13	Liberty Ridge	0(0)	2(1)	2(1)	3(0)
12	Camp Creek	0(0)	1(1)	3(2)	2(1)

*( ) Number of cases associated with extremely persistent winds for 7 or more consecutive hours within a 11.25° sector.

[+] See table 2-4 for location.

2.3.2 Southwestern Pennsylvania Border

- Specific data from along the Ohio-Pennsylvania-West Virginia border (where several counties violate NAAQs for sulfur dioxide) suggest that transport of sulfur dioxide emissions from local and long-range sources contributes to violations of the 24-hour sulfur dioxide standard along that border.

The southwestern Pennsylvania border region is very interesting because it represents an area where air quality is strongly affected by emission sources in adjoining and upwind states over which Pennsylvania has no direct control. A summary of the 1978 air quality in the urbanized-industrialized air basins for the entire state (see table 2-11) shows that the monitors in the western air basins (Baden, Beaver Falls, Charleroi, Erie, and Newcastle) had elevated annual concentrations for one or more of the 3 pollutants, namely SO_2, TSP, and $SO_4^=$. Specifically, the Baden monitor near the western Pennsylvania border with Ohio shows an apparent violation of the annual SO_2 NAAQS, a violation of the TSP NAAQS, and concentrations in excess of the Pennsylvania monthly sulfate standard in all 12 months of the year.[3]

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[3] The reliability of the SO_2 violation is uncertain because of the relatively low percent of valid data.

Table 2-10. Number of Cases When the 25 Highest SO_2 Concentrations Were Associated with Extremely Persistent Winds

Plant Network Location	Persistence Criteria	Year			
		1974	1975	1976	1977
Nanticoke	P.F.≥0.90[a]			7	8
North Shore Lake Ontario					
Bruce Mansfield	11.3°[b]				14
Beaver Valley, PA	22.5°[c]				
	45.0°[d]				
Ft. Martin-Harrison	P.F.≥0.90				
Northern West Va.	45.0°				
Cardinal-Tidd	11.3°	7	6	4	9
	22.5°				19
Kammer-Mitchell	11.3°	3	4	9	11
	22.5°	3	13	15	16
Philo	11.3°	4	6		
	22.5°	13	13		
Muskingham River	11.3°	10	6	12	7
Kyger-Gavin-Sporn	11.3°	6	11		
Amos					
Big Sandy	11.3°	1	5	11	5
Tanners Creek	11.3°	5	9	15	13
Lawrenceburg, IN	22.5°	15	19	20	21
Clifty Creek	11.3°	8	15	16	10
Madison, IN					
Rockport	11.3°				
Breed	11.3°	9	8	18	10
Sullivan, IN					
Paradise					
Cumberland	11.3°			7	3
Cumberland City, TN	22.5°			4	
	45.0°			16	
Allen	45.0°			15	19
Memphis, TN					
Widows Creek					
Kingston					

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[a] persistence factor - ratio of resultant to average wind speed

[b] floating direction sector with maximum direction difference of 11.3° in 7 consecutive hours

[c] fixed direction sector where directions must be within 22.5° for 7 consecutive hours

[d] fixed direction sector where directions must be within 45.0° for 7 consecutive hours

Table 2-11. 1978 Annual Average SO_2, $SO_4^=$, and TSP Concentrations at the COPAMS Sites

Site	SO_2 (ppm)	$SO_4^=$ ($\mu g/m^3$)	TSP ($\mu g/m^3$)
Allentown	0.018(45)[a]	11.7(9)[b]	46
Baden	0.033(51)[c]	18.4(12)	103[d]
Beaver Falls	0.021(35)	14.9(10)	71
Bethlehem	0.012(51)	13.6(9)	83
Briston	0.028(20)	9.6(4)	41
Charleroi	0.017(59)	14.3(9)	59
Chester	0.017(57)	11.7(9)	49
Erie	0.023(26)	12.9(7)	72
Harrisburg	0.015(51)	12.3(9)	63
Johnstown	0.012(64)	14.1(10)	77
Lancaster	0.012(22)	12.8(10)	73
Newcastle	0.015(48)	14.0(10)	92
Norristown	0.013(49)	11.0(7)	51
Reading	0.018(71)	12.5(6)	61
Scranton	0.009(62)	11.4(7)	58
Wilkes-Barre	0.012(57)	10.8(8)	71
York	0.012(67)	13.5(10)	118

[a] ( ) in column 2 indicates percent valid data

[b] ( ) in column 3 indicates number of months with ≥ 10 $\mu g/m^3$

[c] greater than annual sulfur dioxide standard (0.03 ppm)

[d] greater than annual primary TSP standard (75 $\mu g/m^3$)

In order to get a better indication of the transport contribution to 24-hour SO_2 concentrations in western Pennsylvania, the special monitoring data in the vicinity of the Ft. Martin-Harrison plants near the southern Pennsylvania border with West Virginia and in the vicinity of the Bruce Mansfield plants near the western Pennsylvania border with Ohio have been analyzed. The 25 highest daily SO_2 concentrations in the Ft. Martin-Harrison plants monitoring network in 1977 (see table 2-12) show a smooth distribution from a high of 62 $\mu g/m^3$ to a low of 25 $\mu g/m^3$; the majority of these elevated concentrations are associated with extremely persistent winds from the southwesterly to westerly directions. The winds were determined from the 62 meter tower at the Kammer-Mitchell plant about 100 km away since on-site meteorological data were not available.

The 25 highest daily SO_2 concentrations in the Bruce Mansfield plant monitoring network in 1977 (see table 2-13) show that the top 6 concentrations stand out from the rest and that the overall magnitudes were

Table 2-12. 25 Highest Daily SO_2 Concentrations in the Ft. Martin-Harrison Plants Monitoring Networks 1977

Date	Concentration ($\mu g/m^3$)	Location	Extremely Persistent Winds*
2/10	62	Stewartstown	220°
2/9	61	Smithfield	212°
2/5	60	Smithfield	304°
2/6	58	Smithfield	270°
2/2	57	Smithfield	200°
2/1	55	Smithfield	240°
7/18	55	Clemmers Farm	-
2/28	50	Smithfield	250°
2/11	46	Halleck	220°
2/7	45	Stewartstown	244°
2/8	43	Smithfield	-
3/1	41	Smithfield	-
2/15	37	Clemmers Farm	280°
3/6	36	Smithfield	280°
1/31	36	Stewartstown	236°
1/30	36	Smithfield	242°
3/3	32	Smithfield	-
2/26	32	Stewartstown	-
7/29	31	Clemmers Farm	-
7/27	31	Clemmers Farm	-
7/20	30	Clemmers Farm	-
3/30	29	Stewartstown	210°
7/21	27	Clemmers Farm	-
7/19	25	Clemmers Farm	-
3/13	25	Smithfield	-

*Average direction for cases of wind directions within 11.3° for 7 consecutive hours at the 62 meter level of the Kammer-Mitchell plants meteorological tower.

considerably higher (298 $\mu g/m^3$ -160 $\mu g/m^3$) than near the southern border. In addition, about two-thirds of the 25 highest daily SO_2 concentrations in the Bruce Mansfield network were associated with extremely persistent winds that were generally from either the easterly or the southwesterly direction.

The distributions of the 25 highest daily SO_2 concentrations in both the Ft. Martin-Harrison and Bruce Mansfield networks between 1977 and 1978 (see tables 2-14 and 2-15) show that the monitor with the largest number of 25 highest concentrations changes from year to year and that about one-half of all the 25 highest concentrations were associated with extremely persistent winds. The last result strongly suggests that transport of SO_2 from sources outside of Pennsylvania contributed to these elevated concentrations. However, the results for the Bruce Mansfield network data also

Table 2-13. 25 Highest Daily SO_2 Concentrations in the Bruce Mansfield Plant Monitoring Network 1977

Date	Concentration ($\mu g/m^3$)	Location	Extremely Persistent Winds*
10/23	298	Route 68	67°
9/7	295	Route 68	-
10/26	276	Route 68	-
8/16	275	Fairview	225°
12/12	257	Fairview	-
8/28	249	Fairview	-
9/15	225	Fairview	94°
12/5	225	Route 68	70°
10/30	222	Route 68	62°
10/24	222	West Beaver H.S.	79°
12/8	216	Route 68	240°
12/16	211	Fairview	-
10/5	209	Route 68	230°
8/5	201	West Beaver H.S.	-
12/17	186	Route 68	78°
8/13	186	Fairview	215°
8/9	184	West Beaver H.S.	-
10/29	183	Route 68	61°
8/8	181	West Beaver H.S.	-
12/29	177	Route 68	-
8/10	172	West Beaver H.S.	-
8/4	169	Route 68	-
8/11	169	West Beaver H.S.	225°
12/13	165	Fairview	210°
8/26	160	Fairview	195°

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*Average direction for cases of wind directions within 11.3° for 7 consecutive hours at the 500 foot level of the Shippingport meteorological tower.

strongly suggest that sources inside Pennsylvania also were contributing to those 25 highest concentrations that were associated with extremely persistent winds from the easterly direction. The annual average SO_2 concentrations in 1977 at all the Bruce Mansfield sites except McTaggart were in excess of the annual NAAQS, primarily because of the large number of elevated 24-hour concentrations in the first half of 1977.

It is of interest to examine the daily SO_2 concentrations on days with excesses of the 24-hour SO_2 standard at the Fairview monitor in the Bruce Mansfield network during the first half of 1977. The Fairview monitor is located about 7 km northwest (upwind) of the Bruce Mansfield plant and about 5 km east of the Ohio-Pennsylvania border, which makes it the best monitor in the network for determining background concentrations due to transport from distant sources. The tabulation of daily SO_2 concentrations

Table 2-14. Distribution of 25 Highest Daily SO_2 Concentrations at the Ft. Martin-Harrison Plants by Monitoring Site

Site	1977	1978
Fairmont	0(0)*	0
Halleck	1(1)	0
Brownsville	0(0)	0
Stewartstown	5(4)	9
Smithfield	12(8)	3
Clemmers Farm	7(1)	13
Total	25(14)	25

*Extremely persistent winds (22.5°) at the Kammer-Mitchell tower (62 meters).

Table 2-15. Distribution of 25 Highest Daily SO_2 Concentrations at the Bruce Mansfield Plant by Monitoring Site

Site	1977	1978
Fairview	8(5)*	10
Mc Taggart	0(0)	5
Route 68	11(7)	9
West Beaver High School	6(2)	1
Total	25(14)	25

*Extremely persistent winds (11.3°) at the Shippingport tower (500' level).

Table 2-16. Daily SO_2 Concentrations ($\mu g/m^3$) on Days with Excesses of the 24-Hour SO_2 Standard at Fairview, McTaggart, and West Beaver H.S. (January-June 1977)

Date	Fairview	McTaggart	West Beaver H.S.
1/6/77	398		367
4/10/77	369	96	237
4/17/77	365	120	165
4/18/77	402	452	247
4/29/77	365	47	37
4/30/77	528	167	241
5/3/77	396	51	74
5/4/77	369	66	275
5/15/77	369	107	96
5/16/77	498	156	220
5/23/77	371	32	m

Note: m = data missing

at the Fairview monitor and at 2 other monitors shows that elevated SO_2 concentrations occurred at the other two monitors besides Fairview in about half the cases, suggesting the presence of a broad plume or large "blob" with elevated SO_2 concentrations depending on the wind conditions (see table 2-16). About half of the days with high concentrations at Fairview during the first half of 1977 were associated with extremely persistent winds from the south as measured at any two of the three sites with suitable wind data, namely, the Kammer-Mitchell or Cardinal-Tidd plant towers and/or the Shippingport tower.

Although, as noted earlier, the SO_2 monitoring data at the Commonwealth of Pennsylvania Air Monitoring System sites are not as complete as one would like, it is still worthwhile to identify the dates of elevated daily SO_2 concentrations and the associated winds at the 3 monitors in the western air basins (see table 2-17). These results are strongly biased toward underestimating the magnitude and frequency of elevated SO_2 concentrations at these 3 sites since only one-third to one half of the possible days of SO_2 and wind data were available. A persistence factor of 0.90 or greater was considered an extremely persistent wind for the entire day.

The number of days per year with elevated daily SO_2 concentrations and extremely persistent winds at the western COPAMS stations during

Table 2-17. Dates of Daily SO_2 Concentrations $\geq 150\ \mu g/m^3$ at Baden and Beaver Falls, and $\geq 100\ \mu g/m^3$ at Erie, and the Associated Winds (Commonwealth of Pennsylvania Air Monitoring System Stations)

Baden				Beaver Falls			
Date	SO_2 ($\mu g/m^3$)	θ (Degrees)[a]	P.F.[b]	Date	SO_2 ($\mu g/m^3$)	θ (Degrees)[a]	P.F.[b]
10/22/74	155	176	0.87	12/11/74	186	144	0.75
10/28/74	159	177	0.64	6/10/75	273	100	0.73
10/29/74	174	157	0.74	11/3/75	149	199	0.96
5/31/75	200	174	0.96	2/9/76	160	206	0.71
11/19/75	185	239	0.47	12/15/76	149	m	m
1/9/76	231	192	0.97	12/30/76	150	208	0.24
1/10/76	189	172	0.89	1/3/77	186	168	0.76
1/12/76	165	243	0.87	1/23/77	161	140	0.78
1/24/76	178	292	0.76				
1/28/76	192	164	0.97				
2/8/76	207	227	0.71	Erie			
2/24/76	199	172	0.96	2/21/75	103	231	0.76
10/17/76	166	326	0.83	4/4/75	133	314	0.99
12/22/76	184	196	0.87	5/2/75	195	271	0.97
1/11/77	220	245	0.94	5/11/75	119	253	0.61
1/19/77	163	219	0.89	7/31/75	127	341	0.53
1/20/77	197	222	0.94	9/8/75	106	339	0.99
12/10/77	232	259	0.98	9/24/75	317	m	m
12/11/77	175	270	0.95	9/25/75	118	m	m
12/22/77	210	210	0.97	9/28/75	153	m	m
12/28/77	160	205	0.93	9/30/75	114	m	m
12/29/77	207	197	0.91	3/20/76	197	243	0.99

[a] Daily average wind direction

[b] Ratio of resultant to mean wind speed

Note: m = data missing

1974-1977 (see table 2-18) shows a distinct preference for the southerly direction sectors at the Baden and Charleroi sites. The results at Beaver Falls and Erie are inconclusive because these sites have the largest number of days of missing wind and SO_2 data, respectively, of the four sites. The results at the Baden site show about three times more cases associated with extremely persistent winds than without while the results at the Charleroi site show about 50% more cases without than with extremely persistent winds.

One of the most prominent multi-day subregional scale SO_2 episodes in the upper Ohio River Basin occurred January 5 and 6, 1977, when the daily SO_2 concentrations were elevated at most of the AEP monitors (see figure 2-11) as well as in the Ft. Martin-Harrison and Bruce Mansfield networks. The meteorological conditions during January 5-6, 1977, produced stagnation and trapping with an alternating flow first down the river valley to the southwest and then up the river valley to the northeast. It may be noted (see figure 2-11) that the concentrations to the southwest are generally higher on the first day than on the second day, while the opposite is generally true to the northeast on the second day. The hourly SO_2 and meteorological data for the Kammer-Mitchell, Cardinal-Tidd, and Bruce Mansfield plant networks (see table 2-19) generally show elevated concentrations throughout January 6 and wind directions becoming extremely persistent from the south. This episode is an excellent example of how stagnation and trapping over a high SO_2 emission density area followed by persistent winds in the winter can produce a subregional scale SO_2 episode with transport into southwestern Pennsylvania.

The Meadowcroft monitor in the AEP Cardinal-Tidd network is located just 2 km east of the Pennsylvania-West Virginia border. The annual SO_2 pollution roses at Meadowcroft for 1975 and 1976 indicate source contributions from the south-southwesterly, north-northwesterly, and easterly directions. The years 1975-1976 were selected because only 10 months of 1977 data were available from AEP at the time it was requested. The pollution rose at Meadowcroft does not seem to indicate a contribution from the Cardinal-Tidd plants to the west-southwest. The spikes in the pollution roses from the three previously mentioned directions suggest transport of SO_2 from sources both outside and inside Pennsylvania to this location. The annual average SO_2 concentrations at Meadowcroft in 1975 and 1976 were 70 $\mu g/m^3$ and 66 $\mu g/m^3$, respectively. While the Meadowcroft monitor did not show any of the 25 highest daily SO_2 concentrations to be associated with extremely persistent winds during 1974-1977, the Fowlerstown and Bethany monitors to the east of the Cardinal-Tidd plants did show SO_2 episodes associated with extremely persistent winds, with concentrations ranging from 174 $\mu g/m^3$ to 231 $\mu g/m^3$. There were seven cases of SO_2 episodes with extremely persistent westerly winds at the two sites in nearly four years of monitoring data.

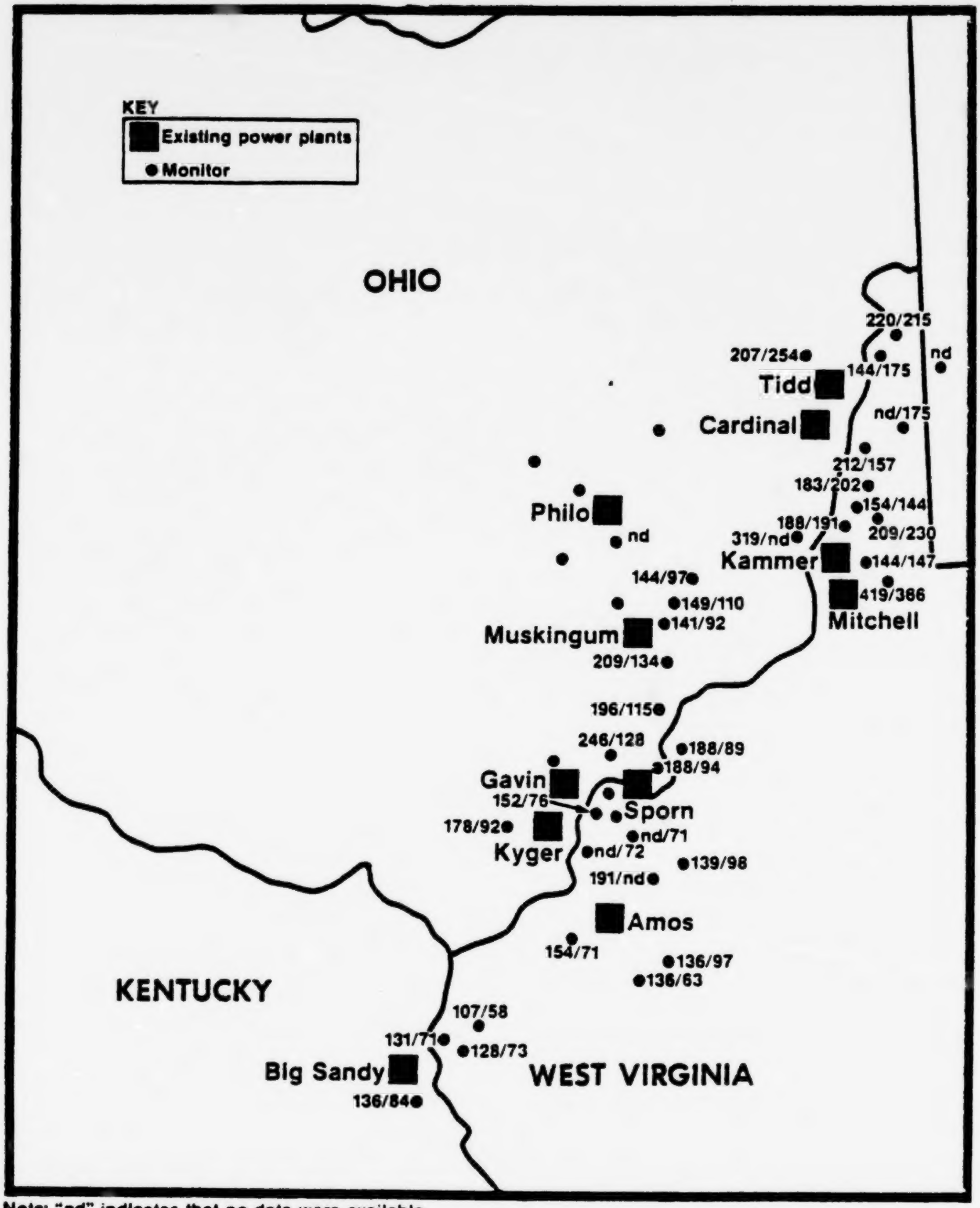
The Pennsylvania Department of Environmental Resources (DER) has recently established SO_2 monitors right on the western border at Georgetown and Florence. Additional border SO_2 monitors and periodic airborne SO_2 measurements during periods of stagnation and persistent winds are required to provide more definitive information for source-receptor relationships and regulatory matters.

Table 2-18. *Number of Days per Year with Elevated Daily SO_2 Concentrations and Persistent Winds at the Western COPAMS Stations (1974-1977)*[*]

Director Sector	Baden		Beaver Falls		Erie		Charleroi	
	Days with Persistence	Days with No Persistence	Days with Persistence	Days with No Persistence	Days with Persistence	Days with No Persistence	Days with Persistence	Days with No Persistence
1 (1°- 45°)	0	0	0	0	0	0	0	2
2 (46°-90°)	0	0	0	0	0	0	0	0
3 (91°-135°)	0	0	0	0	2	3	1	3
4 (136°- 180°)	5	2	1	3	0	0	8	6
5 (181°-225°)	7	0	0	2	2	0	10	15
6 (226°-270°)	4	2	0	0	0	0	1	6
7 (271°-315°)	0	1	0	1	0	0	3	5
8 (316°-360°)	0	1	0	0	0	0	1	1
Total	16	6	1	6	4	3	24	38

Note: For both the days with persistence and the days with no persistence, the persistence factor was ≥ 0.90.

[*] Of the 1461 possible days of SO_2 and wind data (1974-1977), each of the western COPAMS stations had the following number of daily SO_2 and wind data available (SO_2; wind): Baden (532; 1259), Beaver Falls (580; 845-Newcastle), Charleroi (656; 1285), and Erie (206; 1046).


KEY
■ Existing power plants
● Monitor
OHIO
220/215
207/254
144/175
nd
Tidd
Cardinal
nd/175
212/157
183/202
154/144
188/191
209/230
319/nd
Philo
nd
Kammer
144/147
144/97
419/386
149/110
Mitchell
141/92
Muskingum
209/134
196/115
246/128
188/89
188/94
Gavin
152/76
Sporn
178/92
nd/71
Kyger
nd/72
139/98
191/nd
Amos
154/71
136/97
136/63
KENTUCKY
107/58
131/71
128/73
Big Sandy
WEST VIRGINIA
136/84

Note: "nd" indicates that no data were available.

Figure 2-11. 24-Hour average SO_2 concentrations (μg/m^3) at AEP monitors in the upper Ohio River area on 5 and 6 January 1977.

Table 2-19. *Hourly SO_2 and Meteorological Data for the Kammer-Mitchell, Cardinal-Tidd, and Bruce Mansfield Plants During the SO_2 Episode of 6 January 1977*

Site	Parameter	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
KAMMER-MITCHELL:																									
Bowman	SO_2^a	399	352	326	337	337	357	459	446	405	410	389	350	324	439	540	527	433	360	347	303	253	224	211	277
	WS^b	0.9	1.3	2.7	3.6	4.5	5.4	4.9	5.4	4.5	4.0	4.0	4.9	5.8	4.9	4.5	3.6	2.7	2.2	3.1	3.1	3.1	3.1	4.0	3.6
	WD^c	124	171	175	183	182	188	191	194	195	195	204	210	210	215	206	205	200	198	194	191	181	179	200	211
	TD^d	10	7	8	9	4	2	0	-4	-6	-9	-10	-10	-9	-9	-9	-9	-8	-7	-6	-4	-3	-2	-1	-3
CARDINAL-TIDD:																									
New Alexandria	SO_2^a	133	89	365	1185	496	324	323	232	185	305	305	227	178	133	133	164	201	154	133	125	120	141	211	232
	WS^b	0.9	0.9	0.9	2.2	2.7	4.5	5.4	5.4	5.8	5.4	4.9	3.6	4.0	5.8	5.4	3.6	3.1	2.7	3.1	3.6	3.1	3.1	3.1	3.6
	WD^c	C	C	89	163	167	187	197	197	199	202	207	216	203	222	221	231	211	214	208	206	202	183	190	205
	TD^d	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	-9	-9	-5	-8	-8	-7	-7	-4	1	1	-1
BRUCE MANSFIELD:																									
Fairview	SO_2^a	120	120	120	120	91	713	605	713	515	515	487	600	657	515	346	318	459	233	204	289	346	318	402	398
Western Beaver	SO_2^a	ND	106	106	106	359	540	504	576	576	504	359	359	540	648	395	323	359	359	323	323	323	251	287	215

Note: ND = no data; C = calm

^{a} ug/m^3

^{b} WS= wind speed (ms^{-1})

^{c} WD= wind direction (degrees from the north)

^{d} TD= temperature difference

2.4 Sulfates and Total Suspended Particulates

Sulfates and total suspended particulates (TSP) are discussed as one class because sulfates are by conventional definition the total water-soluble species in the total suspended particulates sample. With sulfates and TSP, the subtopics of most importance in the context of the ORBES objectives are (1) the locations and causes of nonattainment of the Pennsylvania sulfate standard and the NAAQS for TSP, (2) the contribution of sulfate to the PSD Class II increment and the nonattainment of the secondary TSP NAAQS at individual locations, (3) the long range transport contribution of sulfate and TSP to regional sulfate and TSP concentrations, (4) the $SO_4^=$/TSP concentrations in the southwestern Pennsylvania border region, (5) the contribution of $SO_4^=$ episodes to annual average concentrations, and (6) the source-receptor relationships suggested by the analysis of the emissions, air quality, and meteorological data bases.

2.4.1 Contribution of Sulfate to the PSD Class II Increment and Nonattainment for TSP

- Data indicate that sulfates are a major contributor to the elevated TSP levels in the ORBES region. During the period between August 1977 to October 1978 measurements at least three regional monitoring stations indicated that elevated sulfate concentrations contributed to TSP nonattainment since the 24-hour secondary standard would not have been violated if the sulfate concentration was subtracted from the TSP concentration.

- During this same period, there were 6 cases in the ORBES region (out of the 21 cases observed in the eastern U.S.) in which the sulfate concentrations caused the 24-hour secondary standard to be exceeded.

Probably the best source of high quality $SO_4^=$ and TSP data at rural locations in the 6 ORBES states, as well as in the entire northeastern United States, is the SURE Phase II data. The SURE II $SO_4^=$ and TSP data were screened for the number of critical $SO_4^=$ and TSP concentrations by site during the full period of network operation (August 1977 to October 1978). It should be noted that only stations 1-9 (recall figure 2-5) operated continuously for the entire period and that the other stations operated only during 6 selected months (August and October 1977 and January, April, July, and October 1978). The critical $SO_4^=$ and TSP concentrations of interest are the 24-hour Class II TSP increment (37 $\mu g/m^3$) and the 24-hour secondary TSP NAAQS (150 $\mu g/m^3$), respectively.

The distribution of critical $SO_4^=$ and TSP concentrations by site in the SURE II data (see table 2-20) shows a total of 30 cases of TSP $\geq$ 150 $\mu g/m^3$ and 17 cases of $SO_4^= \geq$ 37 $\mu g/m^3$ within the ORBES region. The site in the region with the largest number of critical TSP concentrations is Sullivan, Terre Haute, IN and the site with the largest number of critical $SO_4^=$ concentrations is Philo, Zanesville, OH. In addition, there were

Table 2-20. Distribution of Critical $SO_4^=$ and TSP Concentrations by Site in the SURE II Data (August 1977-October 1978)[a]

Site	TSP >150 μg/m^3	$SO_4^=$ >37 μg/m^3	$SO_4^=$ Contributes to TSP >150 μg/m^3
2	16	2	4
4*	1	7	
5*	4	2	1
6	5	4	1
7	1	2	
8	1		
9*		3	
11		1	
14		3	
16		1	
17*		2	
18*	1	1	1
19		1	
22*	9		3
23*	14		4
28*		1	
29		3	
30	13	1	3
33	1		1
35*	1		
36	8	1	2
43*		1	
46	3		1
47	8		
48	1		
49	1		
52		1	
TOTALS	88	37	21

---

[a] Critical means TSP ≥150 μg/m^3 (24-hour secondary standard) and $SO_4^=$ ≥37 μg/m^3 (24-hour Class II increment for PSD).

*Sites in ORBES region. See figure 2-5 and table 2-6 for map and location key.

9 cases when the $SO_4^=$ concentration contributed to TSP nonattainment in the sense that if the $SO_4^=$ concentrations were subtracted from the TSP concentration, the TSP concentration would be less than the standard (150 $\mu g/m^3$).

The significance of the above results can be further strengthened by an analysis of the distribution of emissions near the SURE II monitoring stations with critical $SO_4^=$ and TSP concentrations. The emissions information was taken from the SURE II emission inventory for the entire eastern U.S.; emission data are recorded for individual 80 km x 80 km grid cells. The distribution of SURE grid cell total emitted particulate (TEP) or sulfur dioxide (SO_2) emissions near monitoring stations with critical $SO_4^=$ and TSP concentrations (see table 2-21) shows that the majority of the critical values occurred at stations whose grid cell TEP or SO_2 emissions were in the lower ranges (categories 1-3). Simple model calculations show that TEP or SO_2 emissions in these lower ranges are not likely to produce $SO_4^=$ and TSP concentrations of the magnitude of the critical values. In addition, the SURE II monitor locations were carefully selected to avoid the direct influence of sources, and the data were screened to exclude samples due to fugitive dust. The implication of these results is that transport of $SO_4^=$ and TSP over distances of at least 80 km (the emission grid size) was responsible for the elevated concentrations.

2.4.2 Long Range Transport Contributions

- Assuming that sulfate concentrations are a good measure of the contribution of nonlocal sources to local TSP measurements, long-range transport of sulfates over several hundred kilometers contributed between 15 to 20% of the total annual TSP concentrations in the upper Ohio River region during the period 1975 to 1977.

- Under sulfate episode conditions, sulfate concentrations can exceed 30 $\mu g/m^3$ over a 24-hour period, and the $SO_4^=$/TSP ratios can range from 20-45%. This fact suggests that long-range transport contributes 20-45% of the total TSP measured concentration under such episodic conditions.

The long range transport contributions to sulfate concentrations at a particular location are in a sense more difficult to determine than for sulfur dioxide. Some of the reasons for this greater difficulty are the lack of day-to-day continuity in conventional sulfate monitoring due to the 6-12 day sampling schedule, the multi-day regional character of sulfate episodes, and the lack of concurrent meteorological data at most sulfate monitoring stations. Fortunately, the SURE Phase I data base overcomes all three of these basic difficulties to an extent because the data base consists of daily sulfate measurements with concurrent meteorological data at 10 sites distributed over a region, namely, the northeastern United States. However, the number of stations is too small to perform a detailed and rigorous analysis of transport. One simple analysis that can be performed is the association between elevated sulfate concentrations and the meteorological conditions that produce transport in the boundary layer, namely, extremely persistent winds.

Table 2-21. Distribution of SURE Grid Cell Emissions Near Monitoring Stations with Critical $SO_4^=$ and TSP Concentrations (August 1977-October 1978)

		Number of Stations and Times They Measured Critical Concentrations			
Category Number	Range of TEP or SO_2 Emissions[a]	Within Emission Range[b]	TEP≥150 $\mu g/m^3$ TSP[c]	Within Emission Range[d]	$SO_2 > 37 \mu g/m^3$ $SO_4^=$[e]
	(g/s)				
1	>500	5	31	6	14
2	500 - 1,000	2	9	2	3
3	1,001 - 5,000	9	37	6	8
4	5,001 - 10,000	1	1	1	1
5	10,001 - 15,000	0	0	2	9
6	15,001 - 20,000	0	0	1	2
TOTAL		17	78	18	37

[a] TEP emissions for grid cells containing monitors with TSP concentrations exceeding the 24-hour secondary standard (150 $\mu g/m^3$) and SO_2 emissions for grid cell containing monitors with $SO_4^=$ concentrations exceeding the class II PSD increment for TSP (37 $\mu g/m^3$)

[b] Number of monitoring stations with TEP emissions in the surrounding grid cells within the stated range

[c] Actual total number of exceedances of 24-hour secondary TSP standard at the stations

[d] Number of monitoring stations with SO_2 emissions in the surrounding grid cells within the stated range

[e] Actual total number of 24-hour sulfate values greater than the Class II PSD increment for TSP at the stations

An examination of the cases when sulfate concentrations were elevated at the SURE I sites and were associated with extremely persistent winds (see table 2-22) shows that at 6 of the 8 ORBES region sites about 25-50% of the cases were associated with transport while the other cases were associated with complex conditions like variable winds or extended calm. These results are not meant to imply necessarily that the extremely persistent winds caused

Table 2-22. Number of Cases When Sulfate Concentrations Were Elevated and Were Associated with Extremely Persistent Winds

Monitor Location	Threshold Concentration ($\mu g/m^3$)	Number ≥ Threshold	Number with EXPER[a]	Number with No Wind Data
Albany, NY[b+c]	15	24	11	4
Scranton, PA[c]	20	19	4	0
Syracuse, NY[c]	12	20	10	3
Wheeling, WV	30	24	9	0
Huntington, WV	25	20	6	0
Lawrenceburg I, IN	30	17	5	1
Lawrenceburg II, IN	30	18	7	0
Madison, IN	30	13	8	1
Rockport, IN	25	18	2	14
Sullivan, IN	12	27	16	0
Collins, IL	20	42	8	19

[a] Extremely persistent winds (EXPER) in this context mean wind directions within a fixed 45° sector for 7 consecutive hours

[b] Based on daily sulfate data at stations in the SURE I program within 15-20 miles of meteorological tower data

[c] Non-ORBES region monitors

the elevated sulfate concentrations in the first place, although an episode to be discussed later on suggests that this can happen; these results merely show that the air containing the elevated sulfate concentrations can come from a considerable distance away and from a well defined direction sector. The number of elevated sulfate concentrations at the SURE I sites (see table 2-22) also shows that 3 sites in the Ohio River region (Wheeling, Lawrenceburg I and II, and Madison) experienced a relatively large number of concentrations in excess of Pennsylvania's 24-hour sulfate standard (30 $\mu g/m^3$) in the year or less of data at these sites (April 1974-March 1975).

If the entire region and longer time periods are examined--for example, the isopleths of three-year average (1975-1977) of AQCR average TSP concentrations (see figure 2-12)--a definite subregion of elevated concentrations (> 75 $\mu g/m^3$) is evident over the upper Ohio River region. It may be recalled

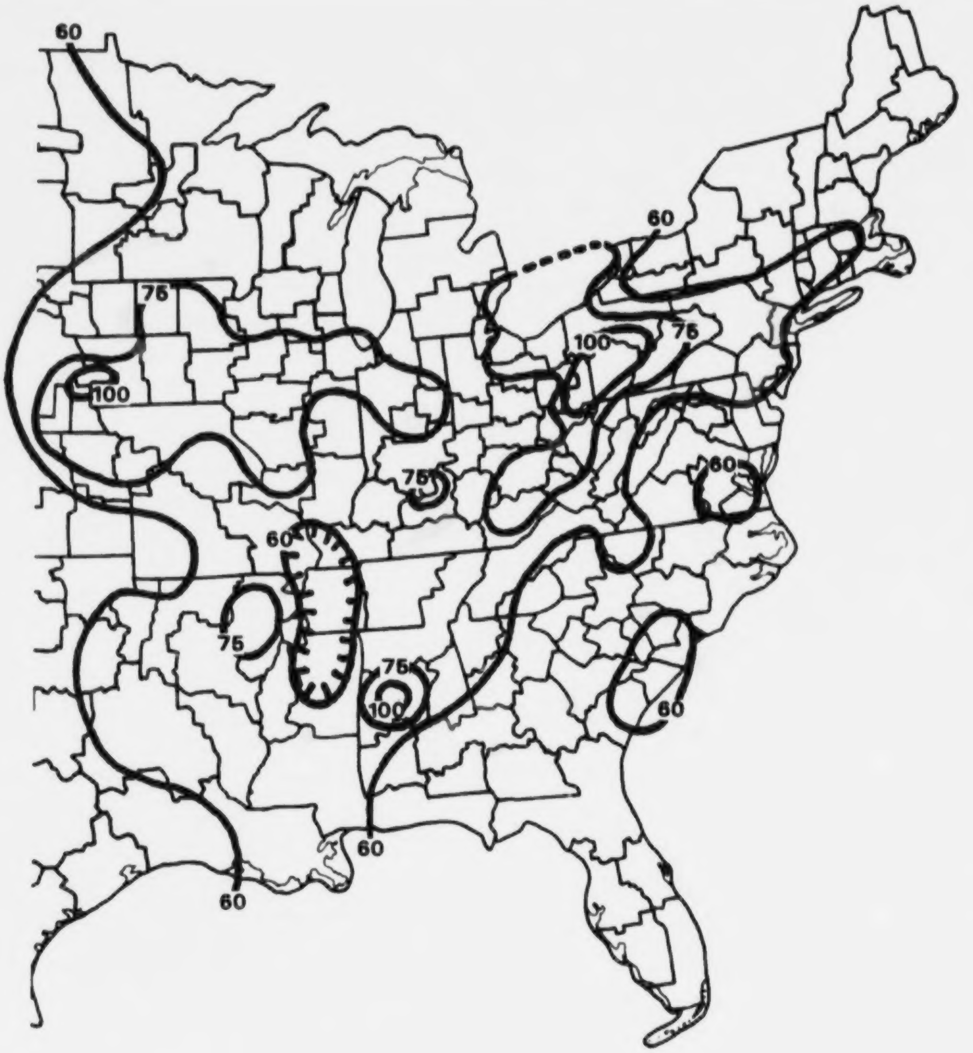

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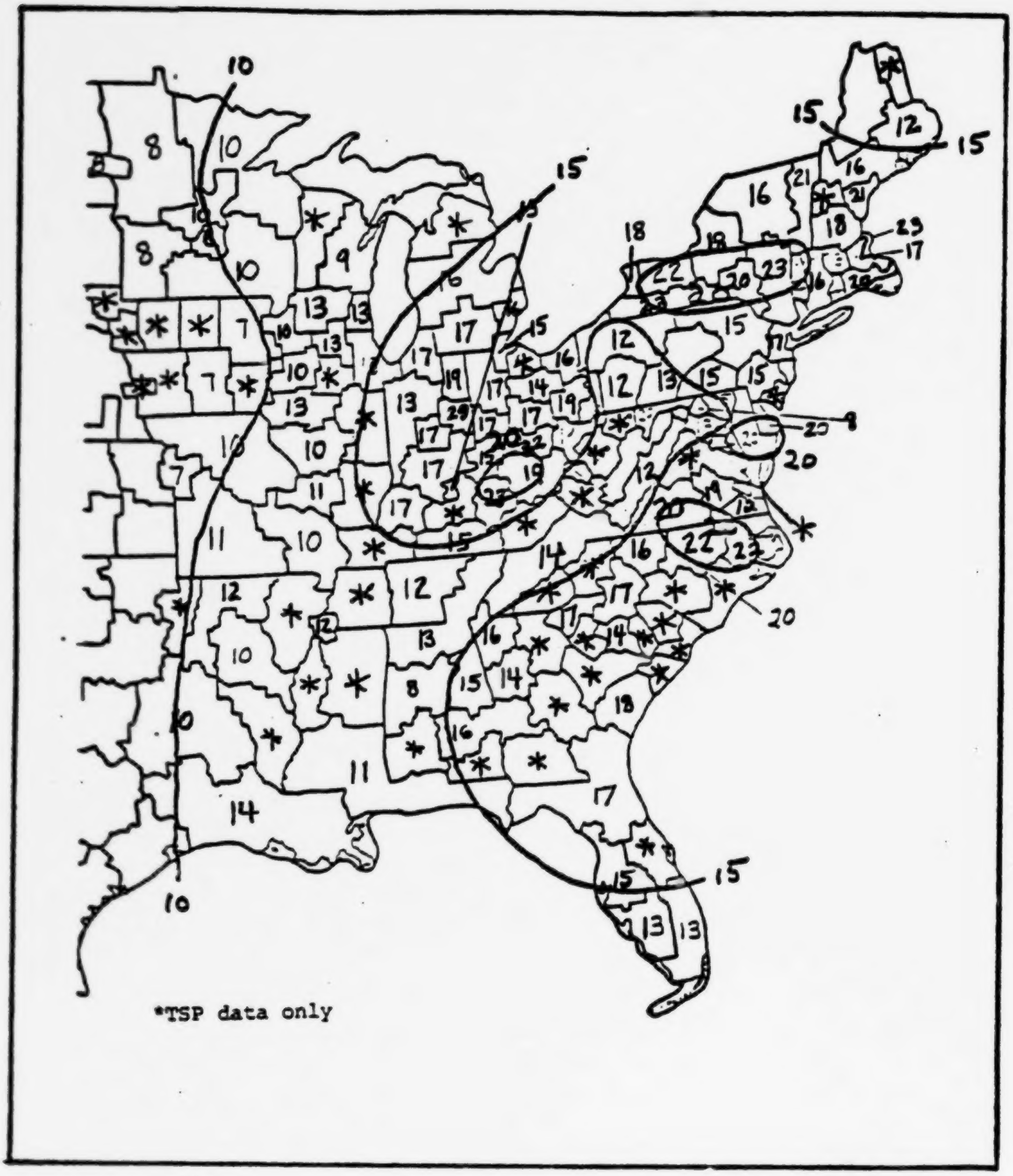
Figure 2-12. Isopleths of three-year average (1974-1977) of AQCR average TSP concentrations ($\mu g/m^3$).

from previous sections that the upper Ohio River Basin contained a number of counties with violations of the primary and secondary TSP NAAQS for both annual and 24-hour periods. The important question in the context of the ORBES objectives is how much does transport of $SO_4^=$ and TSP contribute to this subregion of elevated TSP concentrations and how much do sources near the monitors contribute. Assuming that sulfate concentrations are a good measure of the transport contribution, the relative magnitudes of regional $SO_4^=$ and TSP concentrations should indicate the transport contribution to elevated TSP concentrations. The three-year average (1975-1977) of AQCR average $SO_4^=$ to TSP concentrations (see figure 2-13) shows that about 15% of the TSP concentrations in the upper ORB are contributed by $SO_4^=$.

A similar analysis of the $SO_4^=$ contribution to elevated TSP concentrations in the entire Ohio River region can be made with the SURE II data. The annual average TSP concentrations at the SURE II stations in the 6 ORBES states (see figure 2-14) show values ranging between 28 $\mu g/m^3$ and 59 $\mu g/m^3$. It should be recalled, however, that the averages at only stations 1-9 are true annual averages while those at the other stations represent at most 6 months of data, but with at least one month in each of the 4 seasons. In addition, since some of the TSP concentrations seem anomolously high compared to the nearby stations, it is possible that these higher concentrations are influenced by more "local" sources. The annual sulfate-to-TSP concentrations from the SURE II data (see figure 2-15) show that about 15-20% of the TSP concentrations in the upper Ohio River region are contributed by $SO_4^=$. The question of how far the $SO_4^=$ is transported cannot really be answered from data analysis alone but requires a regional transport model. The sulfate could be transported by extremely persistent winds from a major SO_2 source region upwind of the upper Ohio River region, or just accumulated in a stagnant air mass over the high SO_2 emission area of the upper Ohio River region, or contributed by stagnation and transport in succession.

One of the best documented examples of the transport of sulfates by extremely persistent winds occurred on August 27, 1974. This case study is well documented because the peak of the sulfate episode happened to coincide with the EPA NADB sulfate sampling day and because the episode occurred during the SURE I program; thus, daily sulfate data are available which show the movement of elevated sulfate concentrations from the lower to the upper Ohio River region. The August 27, 1974, case study has been analyzed in detail (cf Tong and Batchelder, 1978). Basically, the episode was not proceeded by the usual stagnation over a major source region, but developed as extremely persistent winds blew along the Ohio River valley with its large number of high SO_2 emission density counties (recall figure 2-6). The isopleths of AQCR average $SO_4^=$ concentrations on August 27, 1974, (see figure 2-16) show a subregion of elevated ($\geq$ 30 $\mu g/m^3$) concentrations over the upper Ohio River region and isolated pockets of elevated concentrations near Indianapolis and Cleveland.

Of the $SO_4^=$ and TSP concentrations and the $SO_4^=$/TSP ratios at selected locations in the upper Ohio River region on August 27, 1974 (see table 2-23), $SO_4^=$ concentrations greater than the Pennsylvania sulfate standard were measured at most locations as were $SO_4^=$/TSP ratios of about 20% to 45%. In fact, the TSP concentration at the Harrison monitor east of Allegheny county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*TSP data only

Figure 2-13. Three-year average (1975-1977) of AQCR average $SO_4^=$ to TSP concentrations (%).

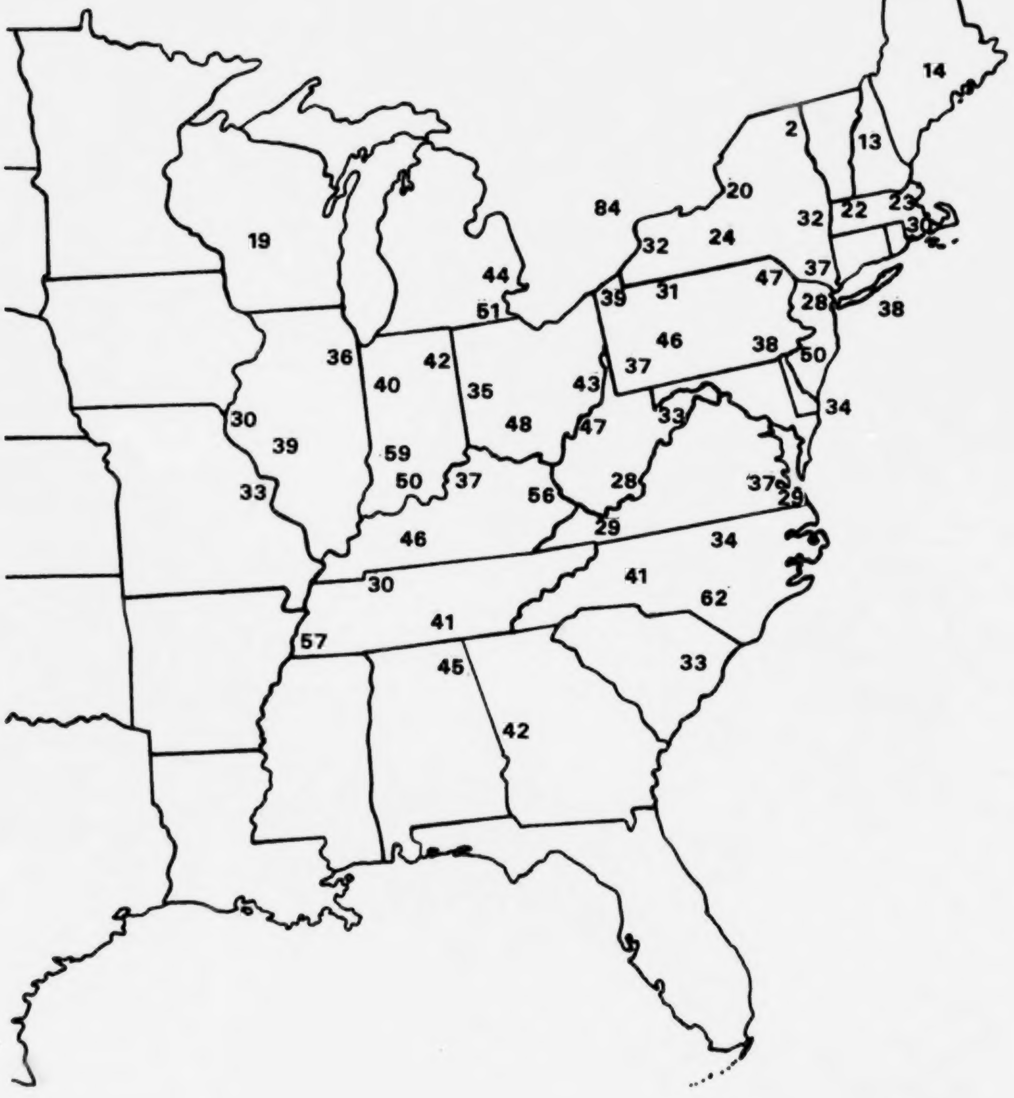
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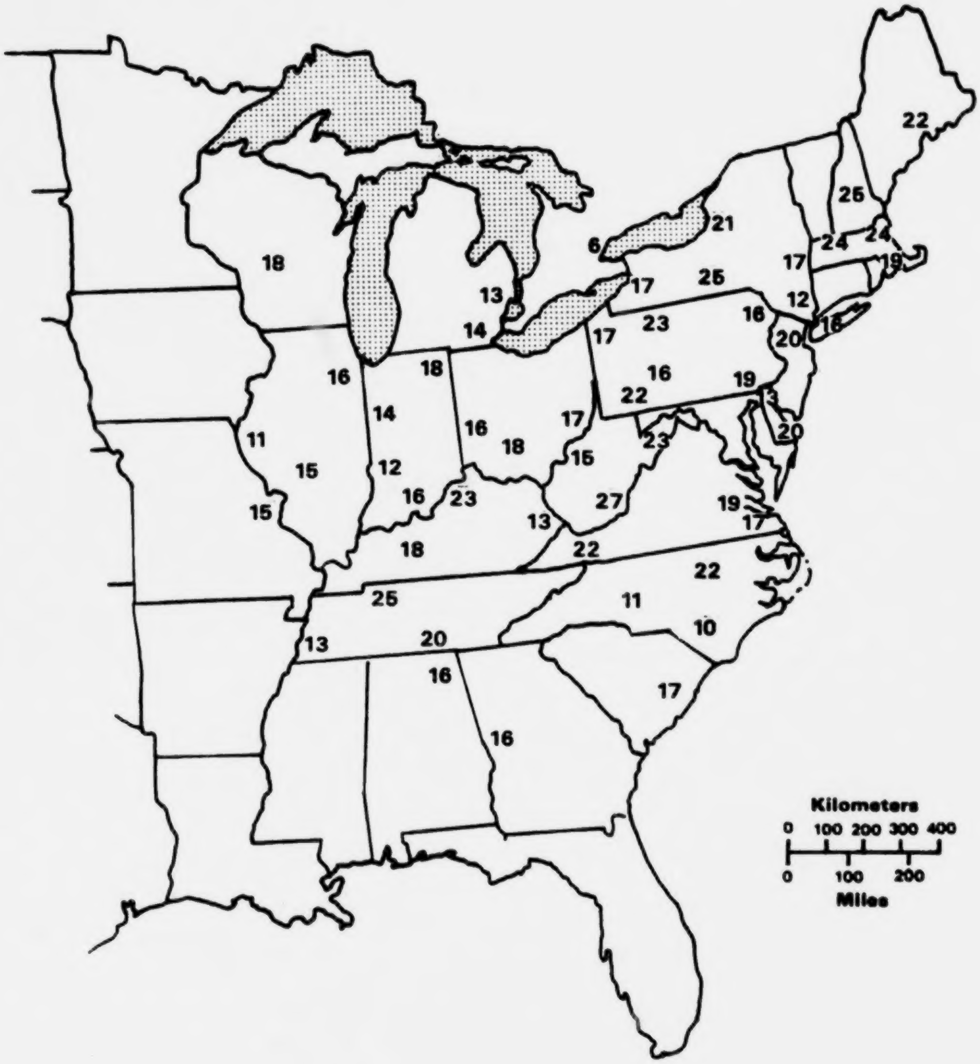
Figure 2-14. Annual average TSP concentrations ($\mu g/m^3$) for SURF II.

even exceeded the primary TSP NAAQS (260 $\mu g/m^3$). These results suggest that transport contributed to elevated $SO_4^=$ and TSP concentrations upwind of Allegheny County and that transport and TSP sources in Allegheny County contributed to the very high TSP concentration downwind of that county. Additional results for the southwestern Pennsylvania border region are presented in the next section.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Kilometers
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0 100 200
Miles

Figure 2-15. Annual sulfate-to-TSP concentrations (%) from SURE II.

2.4.3 Southwestern Pennsylvania Border Region

- In Pennsylvania, long-range transport of sulfur dioxide emissions can contribute significantly (between 25-50%) to widespread violations of the Pennsylvania sulfate standard and to violations of the federal 24-hour TSP secondary standard in that state. Further analysis of data from the southwestern Pennsylvania border area

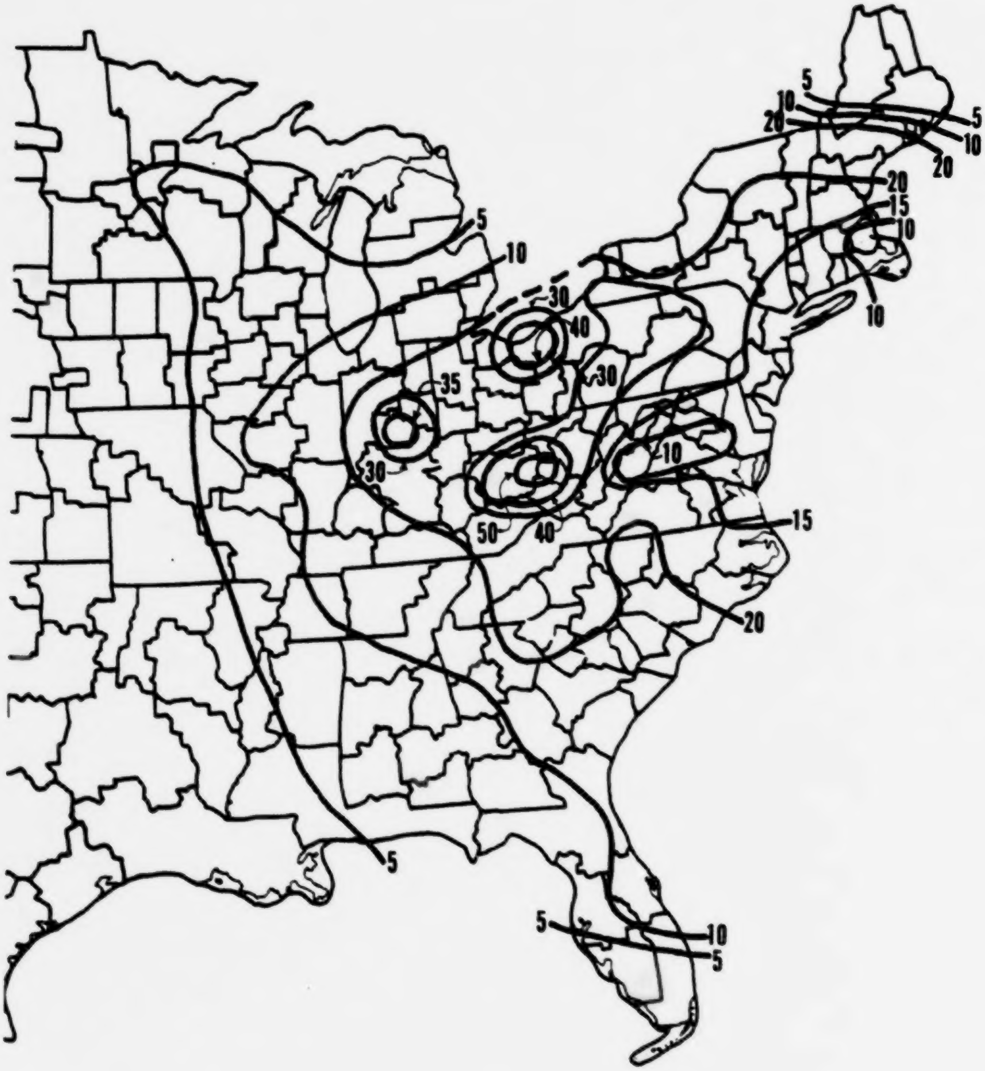


Figure 2-16. Isopleths of AQCR average $SO_4^=$ *concentrations* ($\mu g/m^3$) *on August 27, 1974.*

shows that these high sulfate concentrations are associated more often with long-range transport from the west and southwest (that is, the lower ORBES region) than with transport from the opposite directions.

The initial analysis of long range transport impacts on western Pennsylvania (Niemann and Mahan, 1978) was based on data from Commonwealth of Pennsylvania Air Monitoring System (COPAMS) sites in the southwestern border region that were thought to be the least subject to local sources.

Table 2-23. $SO_4^=$ and TSP Concentrations, and $SO_4^=$/TSP Ratios at Selected Locations on 27 August 1974

Location	$SO_4^=$ ($\mu g/m^3$)	TSP ($\mu g/m^3$)	$SO_4^=$/TSP*
Sharon-Farrell			
Site No. 1	30.3	134	0.23
Site No. 2	31.5	187	0.17
Monongahela Valley			
Site No. 3	32.8	109	0.30
Site No. 5	35.3	143	0.25
Erie Site No. 1	24.7	83	0.30
Scranton, Pa.	37.6	112.6	0.33
Wheeling, W. Va.	36.0	81.2	0.44
Huntington, W. Va.	20.9	56.5	0.37
Beaver Valley**			
Site No. 5	30.4	162	0.19
Site No. 7	34.7	175	0.20
Allegheny County, Pa.			
North Fayette**	n.d.	146	-
Harrison**	n.d.	310	-
Pittsburgh**	39.0	n.d.	-

Note: n.d. = no data.

* The $SO_4^=$/TSP ratios for the 24-hour primary and secondary national TSP standards and the Pennsylvania TSP 24-hour sulfate standard are 0.12 and 0.20, respectively.

**Beaver Valley is in Western Pennsylvania, at the Pennsylvania-Ohio-West Virginia border. North Fayette (suburban-residential) is the county's westernmost monitor; Harrison (suburban-industrial) is the county's eastern monitor; and Pittsburgh (central city - commercial) is in the center of the county.

It was subsequently found that all the sites selected for use in the initial analysis were subject to some problems from improper exposure and/or local sources. Fortunately, Pennsylvania established a small network of $SO_4^=$ and TSP monitoring sites very close to the western and southern borders in the southwestern part of the state. The $SO_4^=$ and TSP measurements at the 9 border sites were made every three days (instead of the normal 6 day interval) during July 1978 to October 1978 in order to overlap with the SURE II program.

A detailed analysis of the results for the border sites was made as part of an advanced phase of the work for EPA and the Commonwealth of Pennsylvania (Mahan, Phillips, and Niemann, 1979). In this section, only some highlights of the results from both phases of the work will be presented in the context of the ORBES objectives.

The number of cases when sulfate concentrations in the initial southwestern Pennsylvania border region were elevated and were associated with extremely persistent winds (see table 2-24) show that about 43% of the cases were associated with transport as opposed to complex meteorological conditions (variable winds), when the extent of transport and the source-receptor relationships are more difficult to quantify. By way of contrast, the initial phase "border sites"--Sharon Farrell, Monongahela, and Erie--show many more cases of elevated TSP concentrations, probably due to the influence of more local sources, than do the special border sites, but the

Table 2-24. Number of Cases When Sulfate Concentrations Were Elevated and Were Associated with Extremely Persistent Winds in Southwestern Pennsylvania (1974-1978)

Monitor and Location	Total Obs.	No. of Days with TSP≥150 μg/m^3	No. of Days with $SO_4^=$/TSP≥0.25	No. of Days with $SO_4^=$≥30 μg/m^3
Sharon Farrell				
Site No. 1	37	26(14)[a]	5(2)	7(4)[a]
Site No. 2	7	7(5)	0(0)	0(0)
Monongahela				
Site No. 3	151	4(3)	75(24)	8(2)
Site No. 5	111	23(5)	33(0)	8(0)
Erie				
Site No. 1	54	2	50	1
Special Border Sites[b]				
Brownsville	39	0	20(8)	2(2)
Frankfort	38	0	28(7)	1(0)
Koppel	37	0	15(8)	3(1)
Midland	38	5	11(4)	4(2)
Mt. Morris	33	1	20(8)	1(1)
New Castle	41	3	4(2)	1(0)
Uniontown	35	0	26(10)	5(3)
Washington	37	0	15(8)	4(3)
Waynesburg	41	0	27(11)	4(3)

[a] Cases with extremely persistent winds (direction within 45° sector for 7 consecutive hours)

[b] July - October 1978

latter show about as many cases of elevated $SO_4^=$ concentrations as the former. (However, there were fewer days of data from the special border sites--4 months of every 3 days--than from the initial "border sites"--3-4 years of every 6 days.) In addition, $SO_4^=$ contributed 25% or more of the TSP concentration at the special border sites on about 50% or more of the days; this fact means that transport of $SO_4^=$ makes a significant contribution to TSP concentrations along the southwestern border in at least the summer season. In general, the special border data show that elevated sulfate concentrations and $SO_4^=$/TSP ratios were associated far more frequently with transport from the west than with transport from the east. In fact, there were no cases during the 4 months of special border data in which $SO_4^=$ levels ($\geq$ 30 μg/m^3) were associated with transport from the east (Pennsylvania) to the west (Ohio and West Virginia).

The frequency of critical $SO_4^=$ and TSP concentrations in the SURE II data, and especially at the sites in the upper Ohio River region, was presented in a previous section (recall tables 2-20 and 2-21). A similar analysis of critical values has been performed for the special border sites. The $SO_4^=$ and TSP concentrations on dates when the TSP concentration was greater than the secondary standard at the special border sites (see table 2-25) show that, in 5 of the 8 cases, the $SO_4^=$ concentration could have been responsible for the TSP concentration being above the standard. In fact, the situations at the Newcastle and Midland sites actually constitute violations of the TSP NASQS since the TSP concentration was greater than 150 μg/m^3 more than once in a year.

The TSP concentrations on dates when the $SO_4^=$ concentration was greater than the PSD Class II increment for TSP at the special border sites (see table 2-26) show only two cases when the TSP concentration was greater than the secondary NAAQS for TSP. Several of the cases when the $SO_4^=$ concentration was greater are already known to be associated with transport during major regional sulfate episodes (i.e., July 19 and August 24, 1978). The frequency of sulfate episodes and their contribution to annual average sulfate concentrations will be discussed in the next section.

2.5 Sulfate Episodes

- Frequently, air mass trajectories associated with major sulfate episodes in the northeastern United States and southeastern Canada pass over the ORBES region, strongly implicating it as a major source region for these episodes.

2.5.1 Source-Receptor Relationships

An examination of the isopleths for the three year average (1975-1977) of AQCR sulfate concentrations (see figure 2-17) reveals that areas of elevated sulfate concentrations exist over and downwind of high SO_x emission states and AQCR's. This fact suggests a source-receptor relationship between elevated sulfate concentrations and high SO_x emissions areas. To determine if this relationship exists it is necessary to examine (1) the long period

Table 2-25. $SO_4^=$ and TSP Concentrations ($\mu g/m^3$) on Dates When TSP ≥ 150 $\mu g/m^3$ in the Special Sulfate Sampling Study (Commonwealth of Pennsylvania) (July 1978 - October 1978)

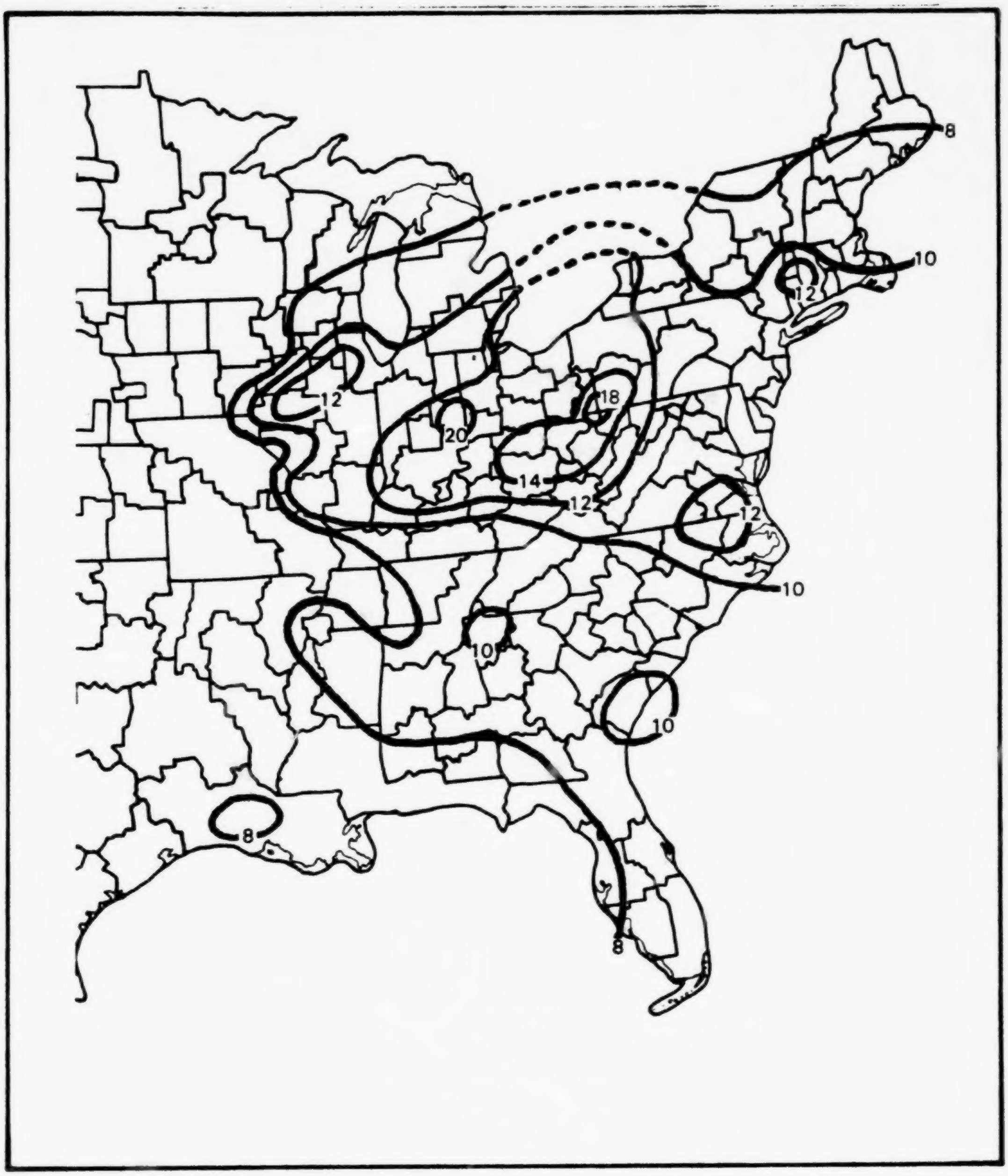
Date	Site	$SO_4^=$	TSP
10/20/78	Mount Harris	27.7	224
7/7/78	Newcastle	28.8	160*
7/19/78	Newcastle	33.2	184
7/19/78	Midland	36.6	153*
8/18/78	Midland	22.9	161*
8/24/78	Midland	26.8	191
9/8/78	Midland	53.3	156*
9/11/78	Midland	33.5	158*

*$SO_4^=$ could be responsible for TSP ≥ 150 $\mu g/m^3$

Table 2-26. TSP Concentrations ($\mu g/m^3$) on Dates When $SO_4^=$ ≥ 37 $\mu g/m^3$ in the Special Sulfate Sampling Study (Commonwealth of Pennsylvania) (July 1978 - October 1978)

Date	Site	$SO_4^=$	TSP
7/19/78	Midland	36.6	153*
9/8/78	Midland	53.3	156*
7/22/78	Washington	39.9	129
8/24/78	Washington	39.9	136
8/27/78	Washington	37.1	99
9/8/78	Washington	39.9	129
9/8/78	Waynesburg	60.4	126
8/24/78	Uniontown	37.0	103
8/24/78	Koppel	42.3	137
8/24/78	Brownsville	37.7	111
9/8/78	Brownsville	45.4	120

*TSP ≥ 150 $\mu g/m^3$


8
10
12
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18
14
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8
8

Figure 2-17. Isopleths of three-year average (1975-1977) of AQCR average $SO_4^{=}$ *concentrations* ($\mu g/m^3$).

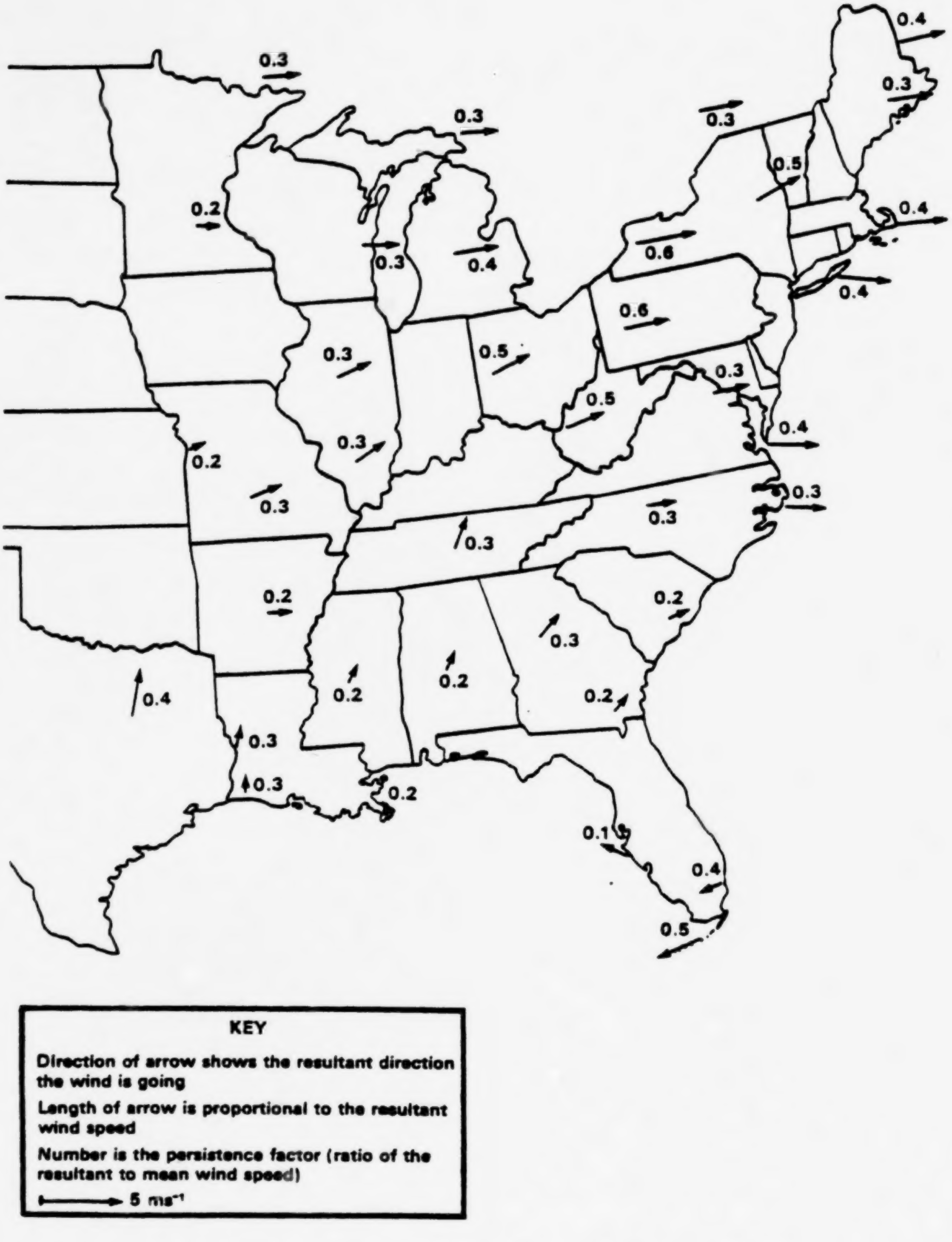
resultant winds, (2) air mass trajectories during episodes, and (3) the frequency of synoptic wind patterns related to sulfate episodes.

The long period (1972-1976) resultant winds and persistence factors at 600 meters above ground at the upper air observing stations in the eastern U.S. generally show that the wind flows from the south in the Gulf Coast states, from the southwest (parallel to the Ohio River) in the lower Ohio River region, and from the west in the upper Ohio River region and extreme northeastern U.S. (see figure 2-18). The persistence factor is the ratio of the resultant wind speed to the mean wind speed and is a measure of the wind direction variability about the resultant wind direction. The persistence factors in the eastern U.S. are generally low (ratios of 0.3 or less), except in western Pennsylvania and New York, which indicates there is considerable variability in transport on a day-to-day basis superimposed on the general west to east transport that emerges from the long period average.

The air mass trajectories during regional sulfate episodes (3-5 days) could, of course, be either generally the same as the long period resultant winds or quite different. It is easy to envision how the air mass trajectories could be quite different from the resultant winds, especially during a period when an extratropical cyclone (low pressure system) traverses the middle of the eastern U.S. However, when the storm track is well north of its normal winter position (mid-eastern U.S.), the air flow over most of the eastern U.S. can be quite similar to that portrayed by the resultant winds if one imagines the air going from one resultant wind vector to the next, and so on. The August 25-28, 1974, sulfate episode period is an example of how closely the pattern of air mass trajectories approximates one defined by connecting the resultant wind vectors with streamlines. The calculated air mass trajectories at 600 meters above ground that were initiated on August 25, 1974, and followed for up to three days show the air flow coming out of the Gulf Coast, closely paralleling the Ohio River, and then crossing the U.S.-Canada border heading northeastward (see figure 2-19). This basic trajectory pattern persisted for several days over most of the eastern U.S. until the trailing end of the cold front crossed the Ohio River Basin and the air flow became northwesterly in that region. The calculated air mass trajectories on August 25, 1974, support the earlier statements about the transport of SO_x emissions and $SO_4^=$ concentrations from the major source region in the lower Ohio River to the upper Ohio River region, where the $SO_4^=$ concentrations were greater than 30 $\mu g/m^3$ over most of the upper Ohio River subregion and the extreme northeastern U.S.

The method used in this study to calculate air mass trajectories has been described previously (c.f., Niemann and Klein, 1979), and a limited comparison of this method to the NOAA Air Resources Laboratory (Heffter) technique, which is in wide use, has recently been made (Niemann and Mayerhofer, 1980).

A comparison of this study's trajectories at 600 meters above ground with the NOAA Air Resources Laboratories' ATAD trajectories on August 27, 1976, initiated from AQCR 72 (Paducah, Kentucky) (see figure 2-20) shows excellent agreement during and at the end of the three-day period. The agreement also was generally good between this study's and the NOAA/ARL


0.4
0.3
0.3
0.3
0.3
0.5
0.2
0.4
0.6
0.3
0.4
0.4
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0.3
0.5
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0.5
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0.2
0.3
0.2
0.2
0.2
0.4
0.3
0.3
0.2
0.1
0.4
0.5
KEY
Direction of arrow shows the resultant direction the wind is going
Length of arrow is proportional to the resultant wind speed
Number is the persistence factor (ratio of the resultant to mean wind speed)
5 ms⁻¹

Figure 2-18. Resultant winds and persistence factors at 600 meters for eastern North America, 1972-1976.

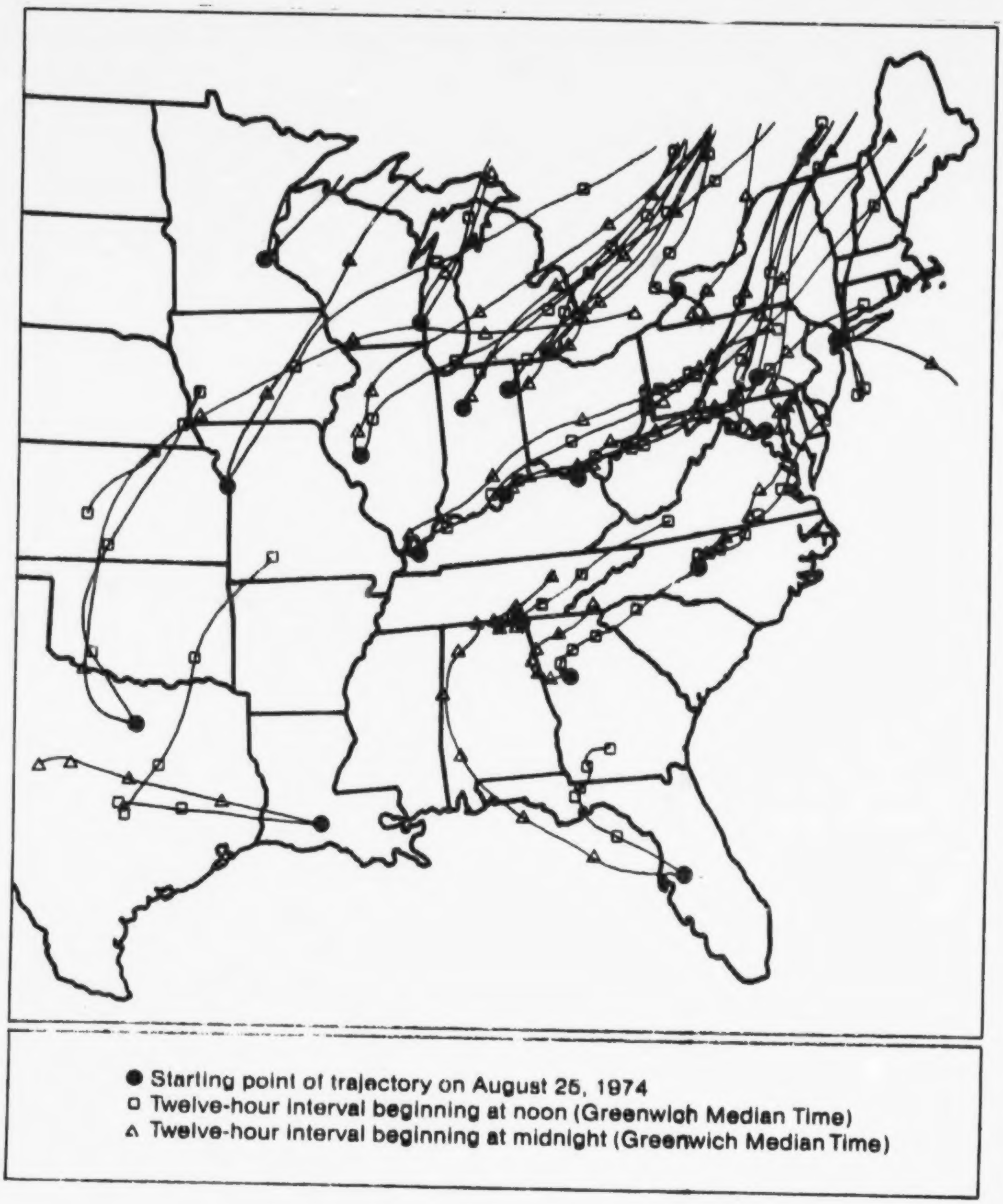

● Starting point of trajectory on August 25, 1974
□ Twelve-hour interval beginning at noon (Greenwich Median Time)
△ Twelve-hour interval beginning at midnight (Greenwich Median Time)

Figure 2-19. Calculated air mass trajectories at 600 meters above the ground, August 25, 1974.

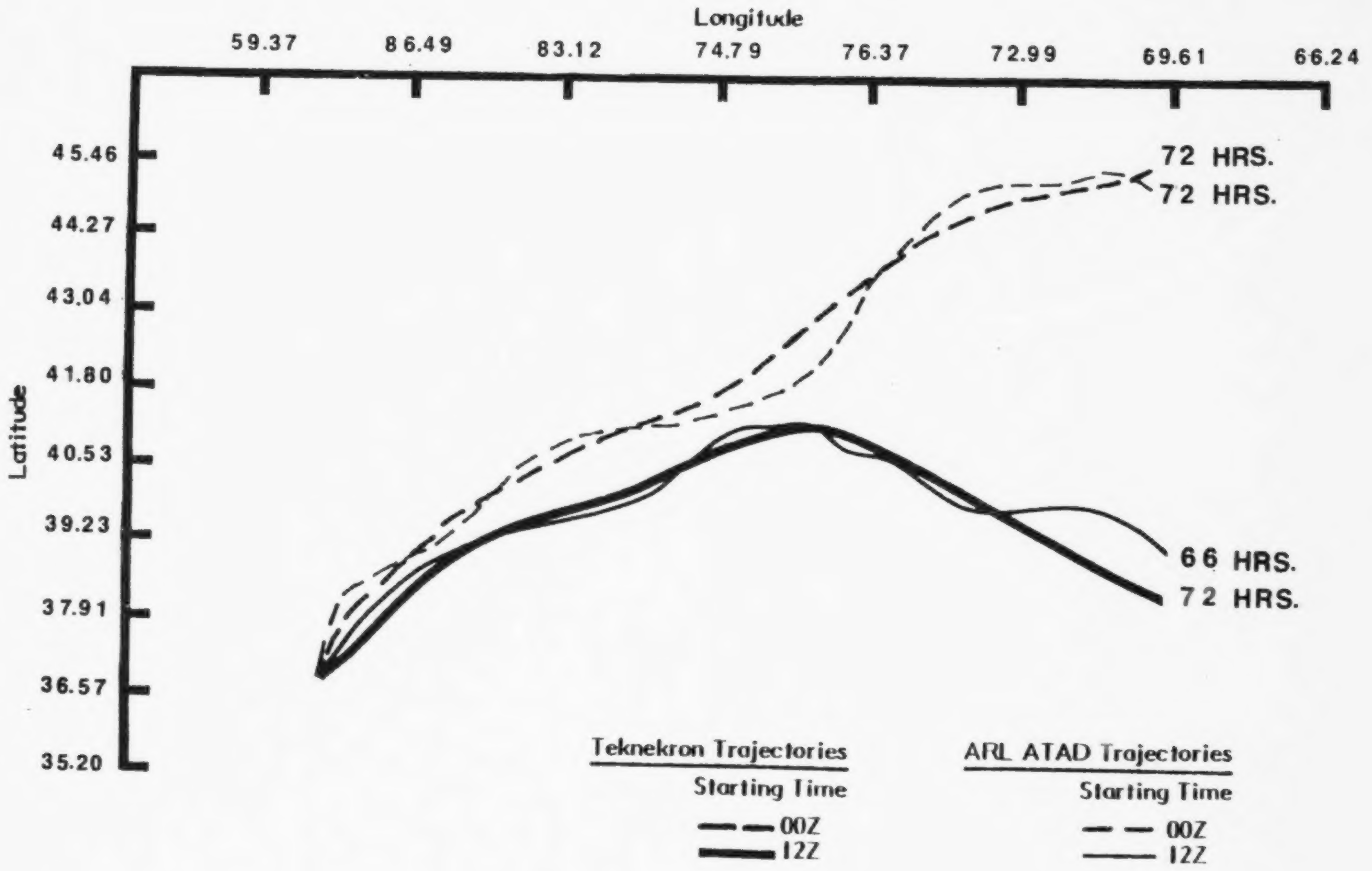


Figure 2-20. Comparison of Teknekron's trajectories with NOAA Air Resources Laboratories' ATAD trajectories on August 27, 1976, initiated from AQCR 72.

trajectories in the other cases selected to include a cross-section of flow complexities, including a complete curl around. The general agreement between the two trajectory models was especially encouraging because this study's model just used winds at individual levels like 600 meters while the NOAA/ARL model is more sophisticated, using winds averaged over the boundary layer, the depth of which changes along the trajectory.

The final meteorological analysis to consider for regional modeling is the frequencies of synoptic weather patterns related to sulfate episodes. The frequencies of synoptic weather patterns related to sulfate episodes are important to estimating the true frequencies of regional sulfate episodes and to computing the seasonal and annual impacts. The frequency of regional sulfate episodes is a lower bound when the episodes are based on EPA NADB data, which is collected only every 6-12 days, and is an upper bound when the episodes are based on synoptic weather patterns since the photochemistry that produces sulfate episodes is not present on every day of the episode weather patterns. The true frequency of regional sulfate episodes lies between the frequency based on sulfate data and that based on weather patterns, but is probably closer to the latter than the former.

2.5.2 Correlation Between Satellite Imagery and Ambient Concentrations

- Regional-scale sulfate episodes often are associated with reduced visibility.

- The isopleths of yearly average visibilities based on airport visual range data show an area of visual range of less than 16 km along the Ohio River valley (see figure 21), which generally coincides with the area of elevated sulfate concentrations of about 8 $\mu g/m^3$ in the SURE II data. The yearly average visibilities outside of the Ohio River valley in the 6 ORBES states are greater than 16 km but less than 24 km.

The trends in airport visual range for stations with suitable data in the Ohio River region have been alalyzed by Husar, et al (1979) and the mean visual ranges were found to have generally declined during 1948-1972. Other data for the period 1960 to 1978 indicate that the annual average sulfate concentrations over the Ohio River also declined, primarily because of a decline in winter season average sulfate concentrations.

In order to more firmly establish the role of elevated sulfate concentrations in visibility degradation within and downwind of the Ohio River region, case studies were made using satellite imagery and sulfate data during episodes. These case studies are reported elsewhere (Niemann and Apodoca, 1980) and only the study with the best data sources, the July 22, 1978 episode, is presented here.

The normal satellite imagery generally shows a milky colored area when sulfate concentrations are greater than about 20 $\mu g/m^3$ in contrast to the bright white color of clouds. Recently, the National Environmental Satellite

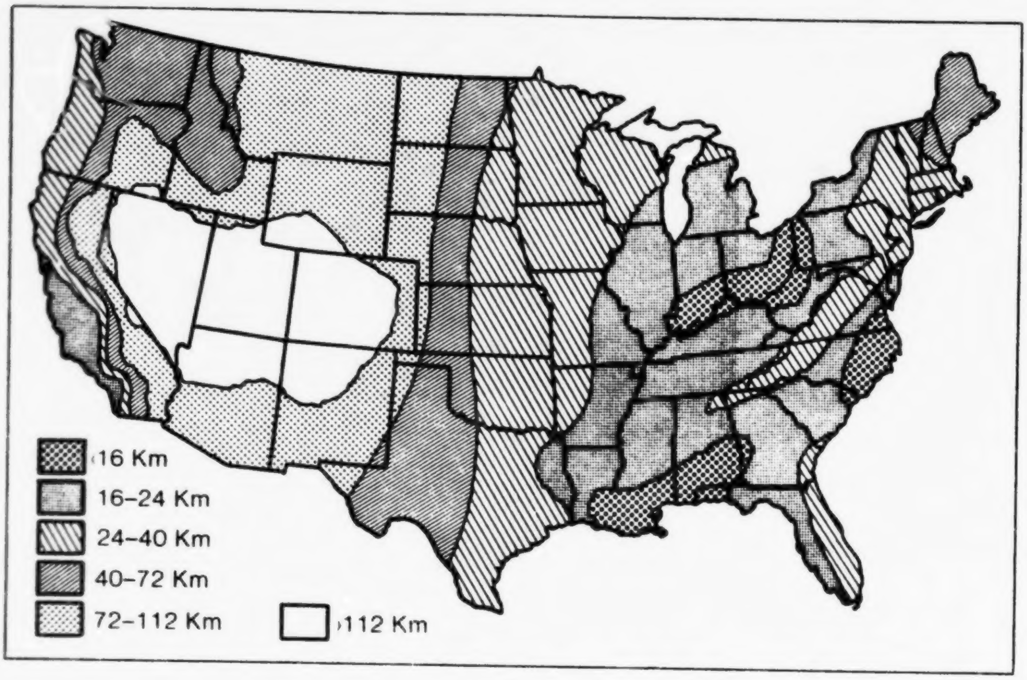


Figure 2-21. Shaded isopleths of yearly average visibilities.

Service (NESS) has developed a technique for digital enhancement of these hazy areas that greatly increases their contrast with clouds to the extent that one can even see the haze intermingled with the clouds. A number of these digitally enhanced satellite photos were hand analyzed so the layperson could easily differentiate the areas of dense haze, perceptible haze, and clouds. An excellent example of this type of analysis was performed for the July 22 episode. This analysis (see figure 2-22) shows a band of dense haze, with bands of perceptible haze to the south and clouds to the north. The largest area of dense haze extended eastward from Virginia to well out over the Atlantic Ocean.

High resolution aerosol sulfur and sulfate data were available for this time period at two locations on the central Atlantic Coast (see figure 2-23). Distinct peaks in concentrations are evident as the episode peaked on that day and as the sulfate was advected from west to east. The mid-day peak in the sulfate concentration at the SURE II Indian River station in Delaware coincides nicely with the area of dense haze in the original satellite photo.

An analysis of the 24-hour average sulfate concentrations from the SURE II network on July 22, 1978, (see figure 2-24) shows the Ohio River Basin area enclosed by a 20 $\mu g/m^3$ contour that generally coincides with the area of dense haze (recall figure 2-22) from Virginia eastward except to the north, where the clouds are probably obscuring the haze. The nearly detached area of haze over Ohio and southern Michigan may have been isolated from the

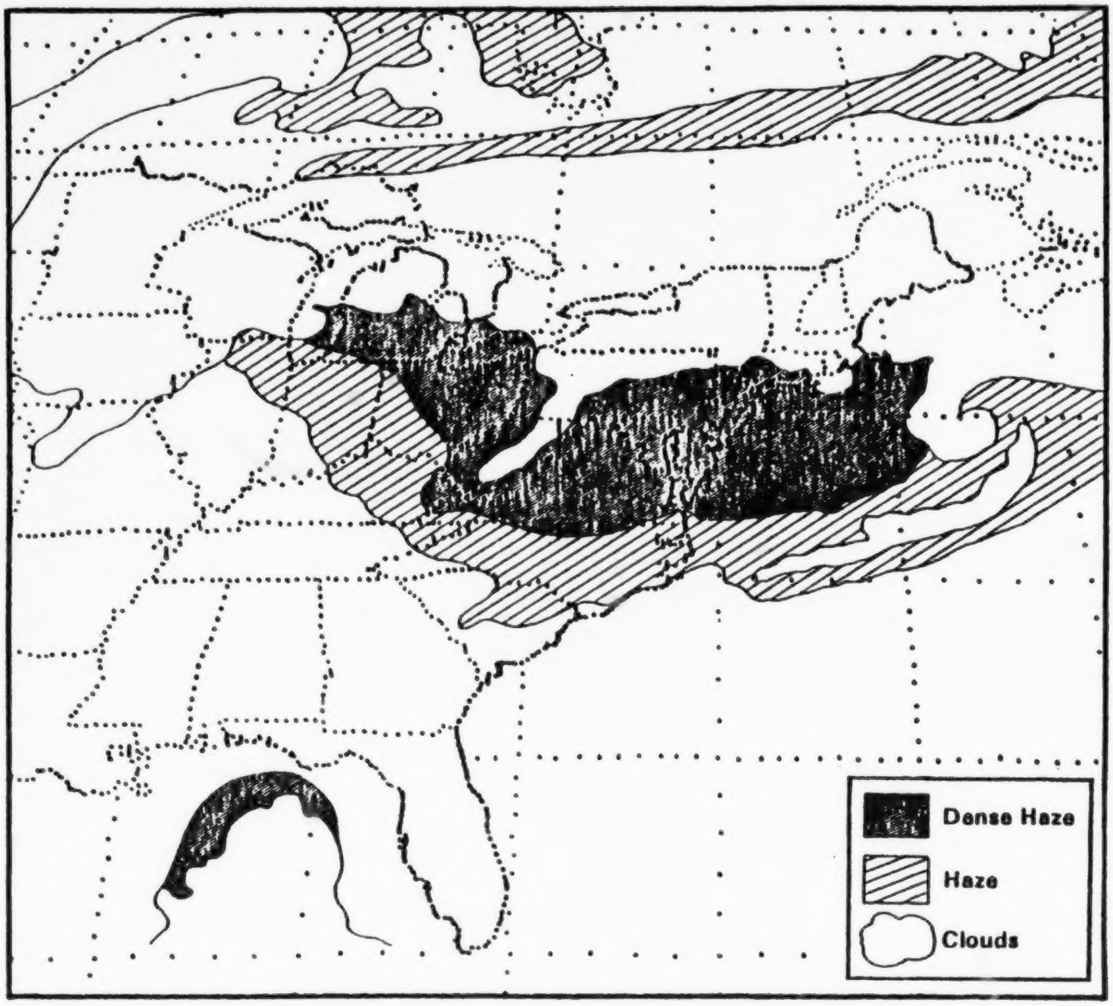
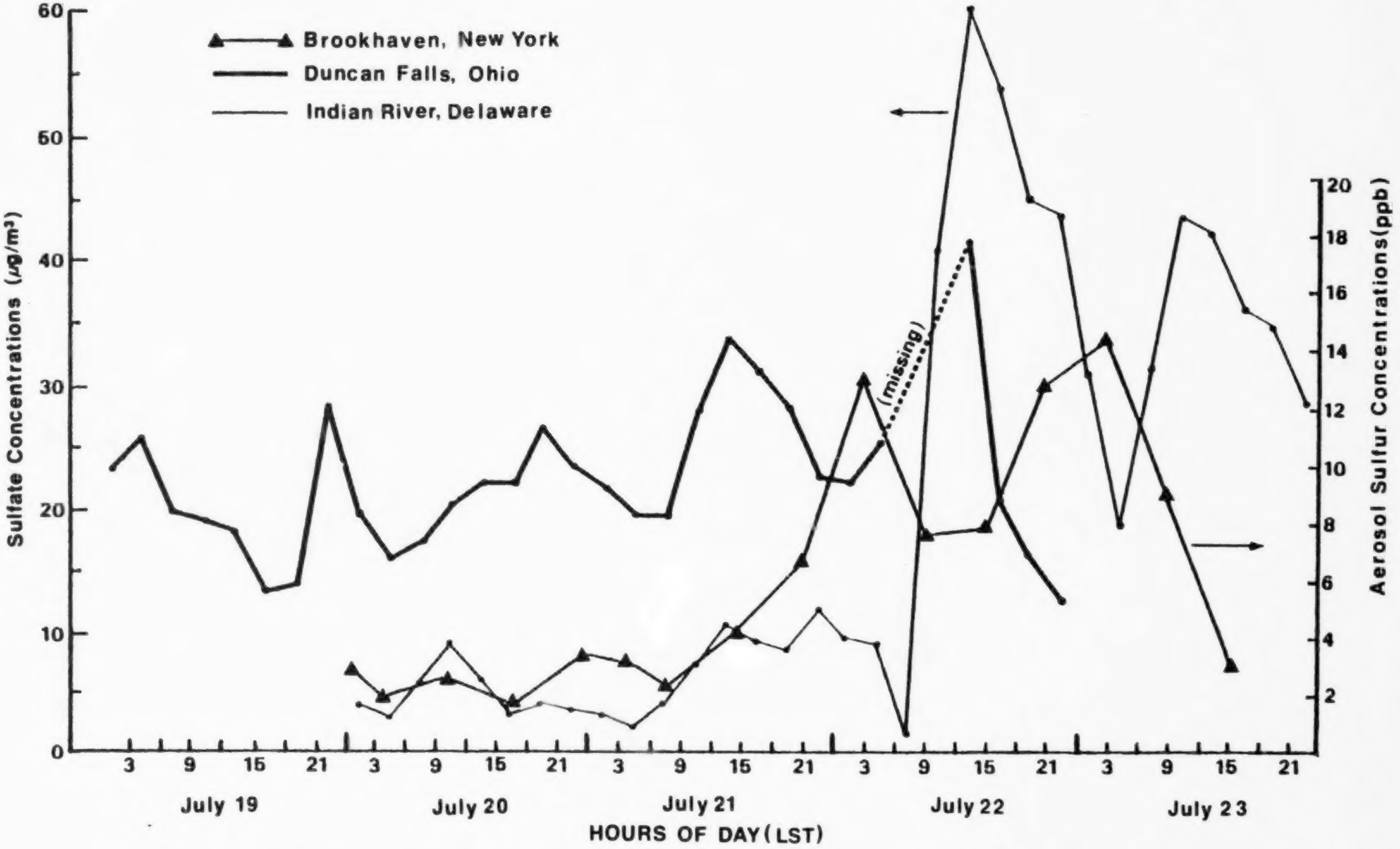


Figure 2-22. Analysis of satellite imagery on 22 July 1978 at 1130 Greenwich median time.

ground by the approaching front in that area since the ground level sulfate concentrations are somewhat less than 20 μg/m^3 and the concentrations aloft producing the haze actually may have been higher.

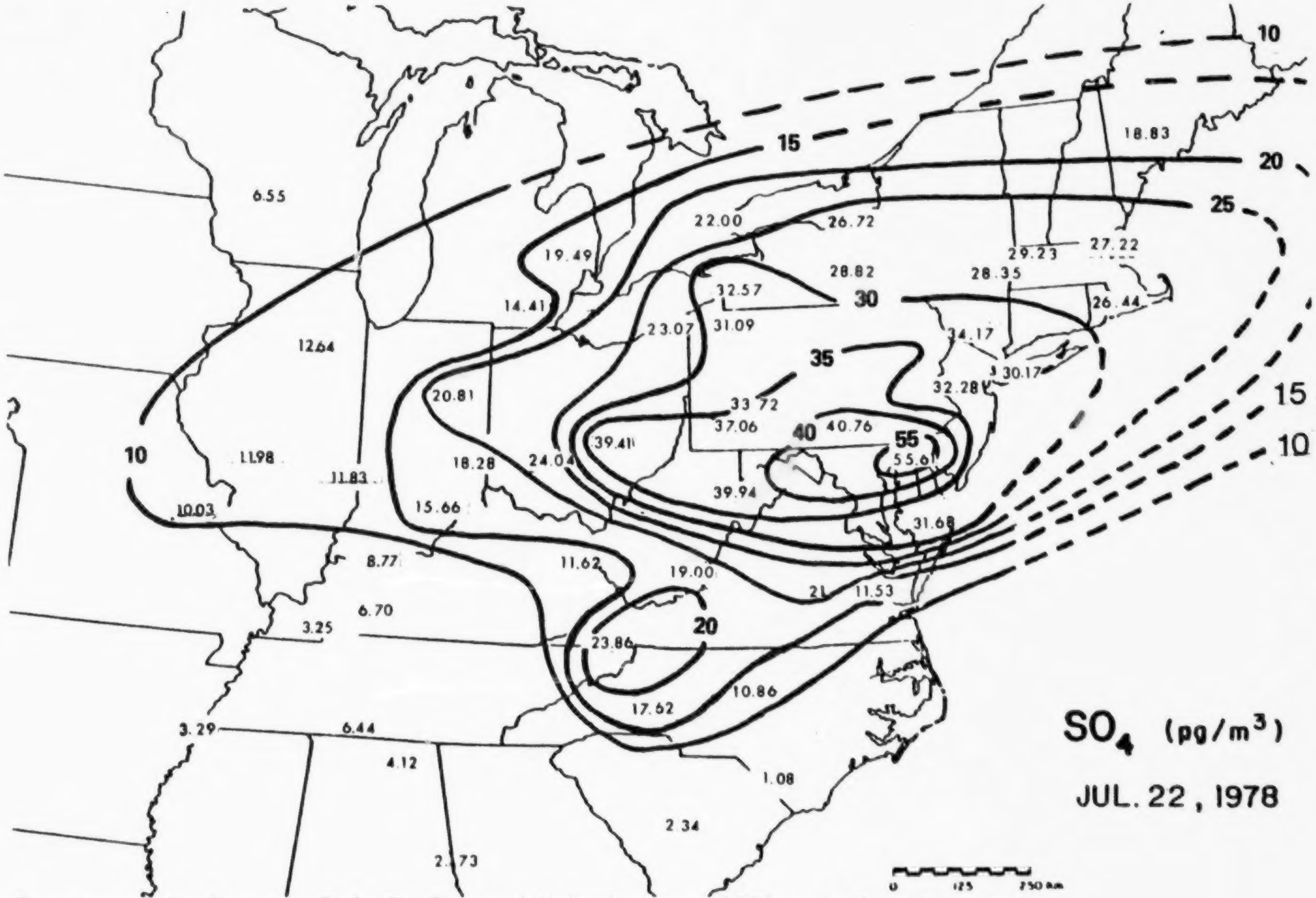
2.5.3 Acidic Deposition

- Acidic precipitation is due primarily to the presence of sulfate and nitrate ions. Precipitation is considered acidic if its pH is less than 5.6, the normal value for natural precipitation. The mean regional pH value during the period September 1978 to May 1979 was 4.1; minimum values were about 3.6. Although



Sources: *Three-Hour SURE II data from Burke, Bowley, and Barnes (1979); BNL filter pack data from MAP 3S Progress Report (1979).*

Figure 2-23. Aerosol sulfur concentrations at Brookhaven, New York, and sulfate concentrations at Duncan Falls, Ohio, and Indian River, Delaware on July 19-23, 1978.



10
15
20
25
15
10
30
35
40
55
20
10
18.83
29.23
27.22
28.35
26.44
22.00
26.72
28.82
19.49
32.57
14.41
31.09
23.07
34.17
30.17
32.28
33.72
37.06
40.76
55.61
39.41
24.04
39.94
31.68
6.55
12.64
20.81
11.98
11.83
18.28
10.03
15.66
8.77
11.62
19.00
21
11.53
6.70
3.25
23.86
17.62
10.86
3.29
6.44
4.12
1.08
2.34
2.73
SO$_4$ (pg/m^3)
JUL. 22, 1978
0
125
250 km

Source: J.C. Barnes, D.J. Bowley and H.K. Burke. 1979. Evaluation of the Capabilities of Satellite Imagery for Monitoring Regional Air Pollution Episodes. NASA Contractor Report 159107. (Concord, Mass.: Environmental Research and Technology, Inc.) August. Figure 3-7.

Figure 2-24. Analysis of 24-hour average $SO_4^=$ levels from SURE network for 22 July 1978.

data are sketchy for determination of the frequency of acid rain, between November 1978 and May 1979, five stations in or near the ORBES region recorded 41 events in which precipitation ph was less than 5.6.

- During the base period, annual wet deposition in the ORBES region tended to be in the middle of the range observed in the eastern United States. In the study region, the range was between 1 and 2 grams of sulfur per square meter per year with the highest measured values occuring immediately downwind in central Pennsylvania. Moreover, a number of wet deposition episodes (low pH and/or high sulfate ion concentrations) appear to be associated with very light rainfall or with rainfall over a limited area at the end of major ambient sulfate episodes.

Concern over the effects of acidic deposition (acid rain) on aquatic and terrestrial ecosystems has increased considerably in recent years. Acidic deposition is just part of the overall problem of atmospheric deposition of beneficial and harmful substances by both wet (precipitation) and dry (i.e., impaction, settling, etc.) processes.

The locations of precipitation chemistry monitors in the 6 ORBES states (see figure 2-25) provide fairly good coverage by monitors in 6 different networks. Unfortunately, different sampling time intervals and other factors make it difficult to integrate all these data for a regional analysis (c.f. Niemann, et al, 1979 for a complete description of the networks and the problems). In addition, the data from some of the networks have not been published for general use. For these reasons, the discussions will be confined to the MAP3S, EPRI, and Region III monitoring data, which were all taken on an individual event (storm) basis and used similar analytical techniques.

The pH distributions from the 5 EPRI stations in or near the Ohio River region (see figure 2-26) show peaks that range from a low of about 3.9 at Rockport, IN to a high of about 4.5 at Lewisburg, WV. The mean pH over the 5 EPRI and 3 MAP3S stations (Champaign, IL, Oxford, OH, and Penn State, PA) in the ORBES region is about 4.1. The mean pH at the EPA Region III Field Office in Wheeling, WV, was about 4.0, but there were only 46 events during November 1978 to May 1979 available to average.

Wet sulfur deposition is another parameter frequently used to characterize acidic deposition. This parameter is the product of the sulfate ion concentration, expressed as sulfur, and the amount of precipitation. The isopleth pattern of wet sulfur deposition in 1977 (see figure 2-27) shows areas of relatively high deposition over southwestern Ontario and St. Lawrence River. A compilation of precipitation chemistry data for the Ohio River region and calculations of wet sulfur depositions for 1977-1978 resulted in average values of about 1 gm/m^2-yr, values which fit in with the 1977 pattern. The Roanoke, IN, and Lewisburg, WV, EPRI stations showed wet

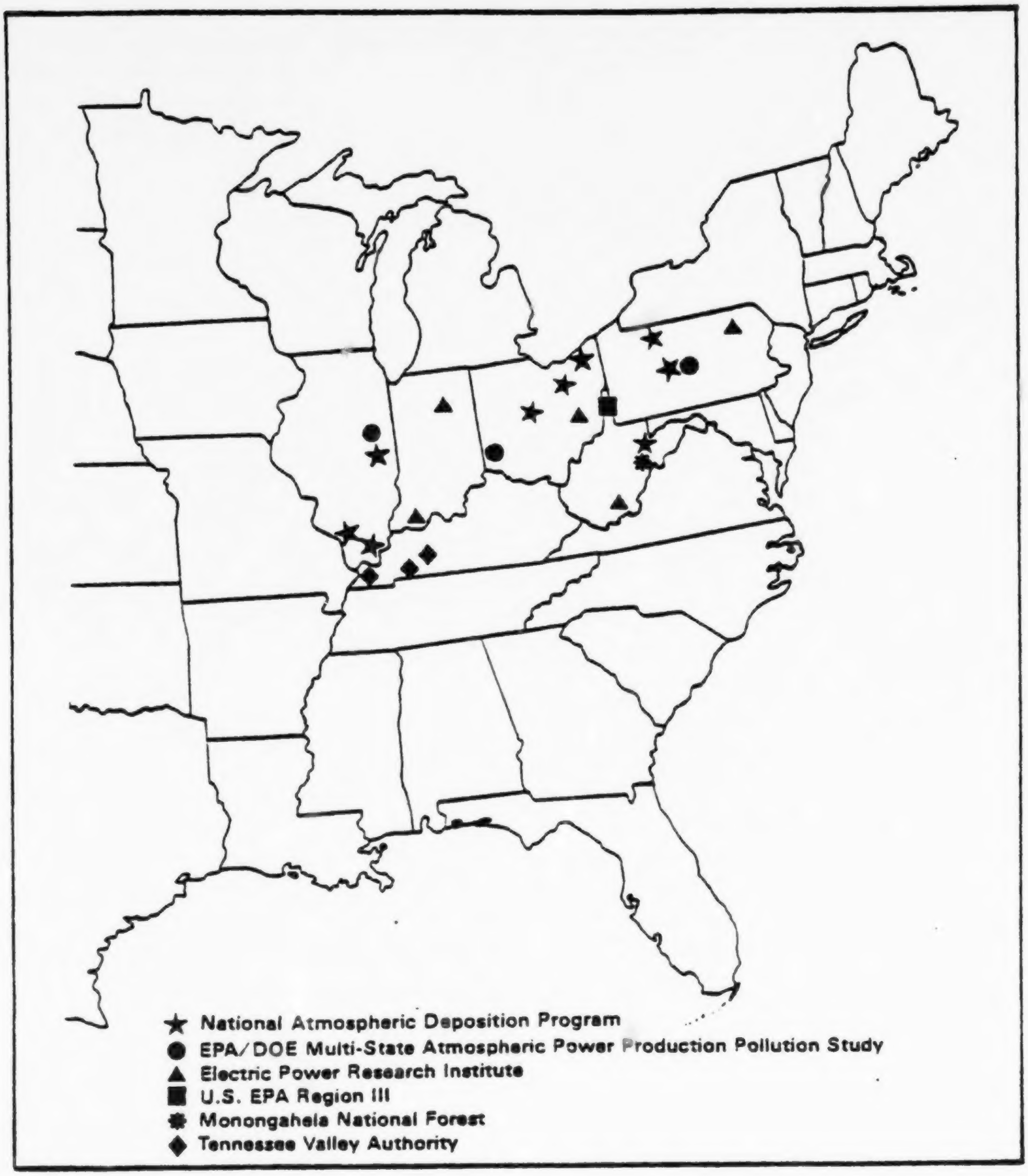

★ National Atmospheric Deposition Program
● EPA/DOE Multi-State Atmospheric Power Production Pollution Study
▲ Electric Power Research Institute
■ U.S. EPA Region III
✸ Monongahela National Forest
◆ Tennessee Valley Authority

Figure 2-25. Selected precipitation chemistry networks in the ORBES region.

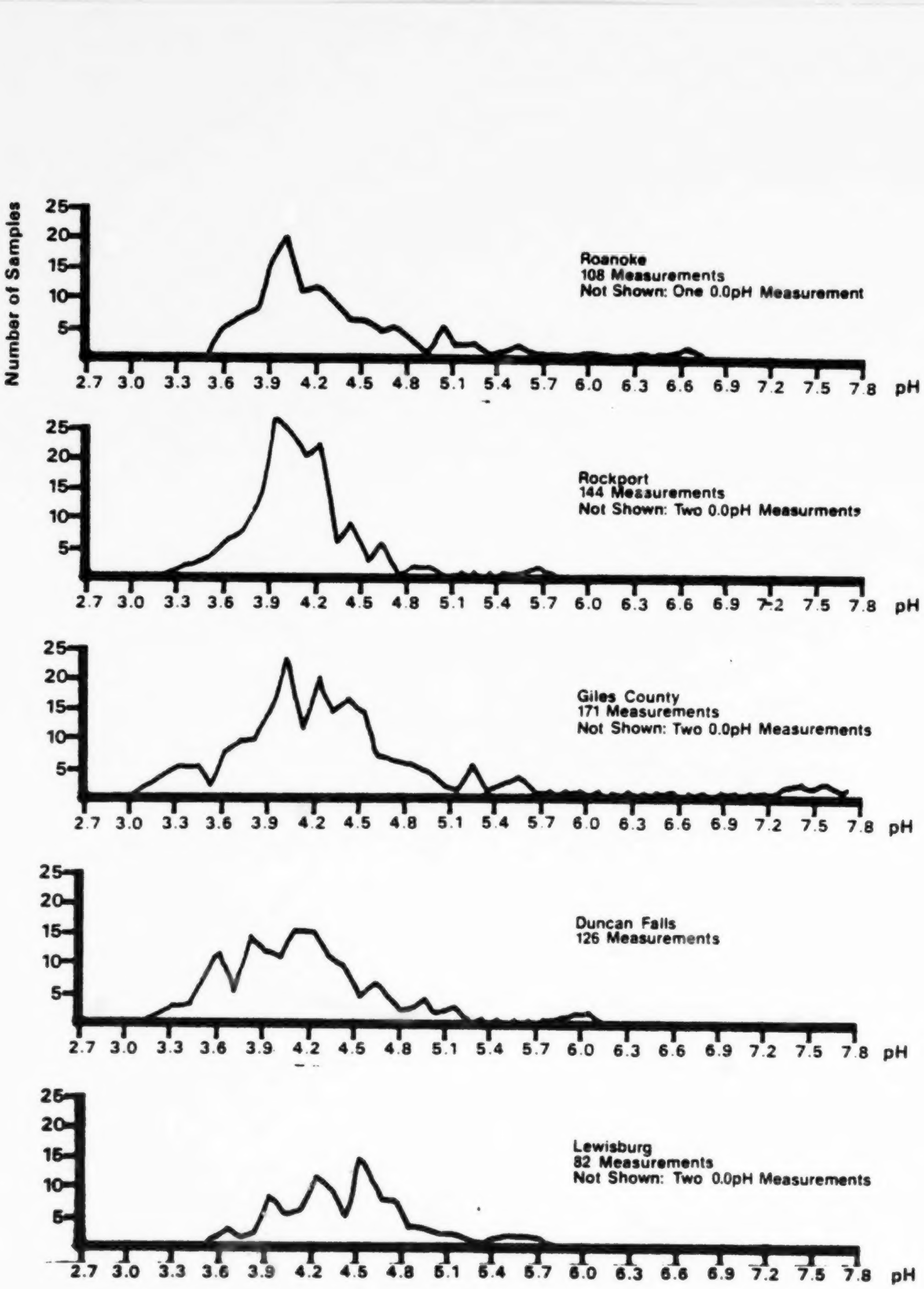
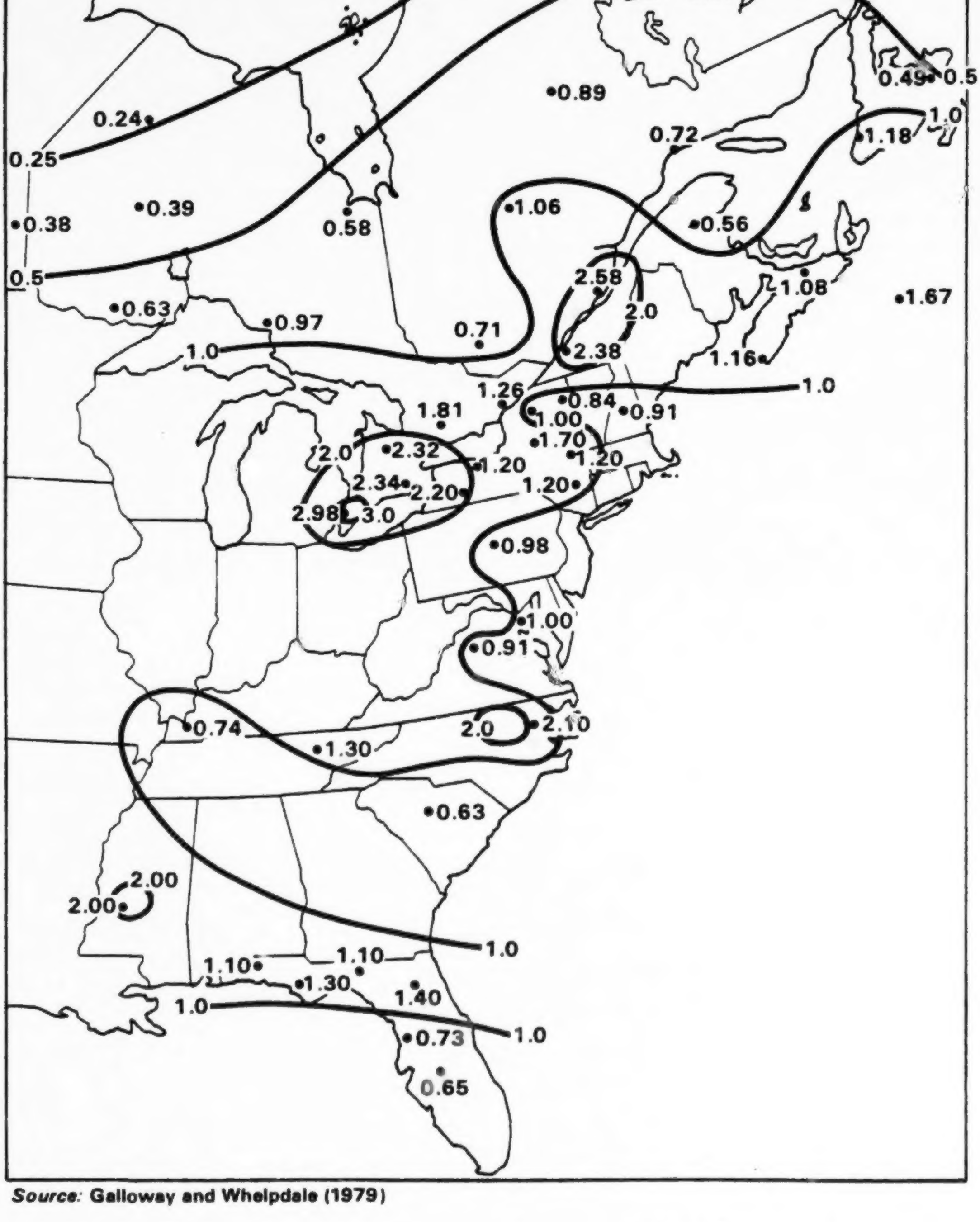


Figure 2-26. pH distributions from EPRI/SURE stations in the Ohio River Basin (September 1978 - May 1979).


0.24
0.25
0.22
0.67
0.49
0.5
0.89
0.24
0.25
1.0
0.72
1.18
0.38
0.39
0.58
1.06
0.56
0.5
2.58
2.0
1.08
1.67
0.63
0.97
0.71
2.38
1.0
1.16
1.26
0.84
1.00
0.91
1.0
1.81
1.70
2.0
2.32
1.20
1.20
2.34
2.20
1.20
2.98
3.0
0.98
1.00
0.91
0.74
2.0
2.10
1.30
0.63
2.00
2.00
1.0
1.10
1.10
1.30
1.40
1.0
1.0
0.73
0.65

Source: **Galloway and Whelpdale (1979)**

Figure 2-27. Wet deposition of $SO_4^=$*-s (g S* m^{-2} yr^{-1}*) in 1977.*

sulfur depositions 4-7 times higher than the average value, depositions that appear to be due to errors in the reported precipitation volumes.

Little data exists on dry deposition rates, even though dry deposition processes are operating about 90-95% of the total time, and even though precipitation is a rather rare occurrence in even the eastern U.S. The reasons for this situation are the lack of generally acceptable measurement techniques and the lack of even "dry bucket" collectors in most networks. As a result, dry sulfur deposition rates usually are calculated from SO_2 and $SO_4^=$ deposition velocities and ambient concentrations. At present in fact, there is greater confidence in the ratio of wet to dry sulfur deposition rates than in the absolute magnitudes of either.

A compilation of the ratios of wet to dry deposition from measurements and calculations by Whelpdale and Galloway (1980) suggests that the ratio is less than one in source (high emission density) regions and greater than one in receptor (low emission density) regions. The ratios of wet to dry sulfur deposition at 3 monitoring sites with both types of data ranged from about 2-7 during 1976-1978; the 3 monitoring sites are at Argonne, IL, Woods Hole, MA, and Chester, NJ, and are part of the Department of Energy's Environmental Monitoring Laboratory Network. In contrast, the ratio of wet to dry sulfur deposition at Ontario Hydro's Wesleyville site on the south shore of Lake Ontario was only 0.1 in 1978. The reasons for the large disparity in results between the DOE/EML and Ontario Hydro data are not known.

2.6 Regional Scale Episodes

One objective of the air quality analysis was to develop the capability to model the distribution of the region's sulfur dioxide, sulfate, and TSP ambient concentrations under both episodic and annual average conditions.

The episode simulation model selected in the ORBES project was the pseudo-spectral technique for solution of the 2-dimensional transport equations for the regional scale. The pseudo-spectral technique was originally applied in the European long-range transport program by Prahm and Christensen (1977) and was adapted to the simulation of regional sulfate episodes in the northeastern U.S. by Teknekron Research, Inc. (Mills and Hirata, 1978). The pseudo-spectral model has been evaluated so far against 5 of the 10 episodes selected to provide a representative cross-section of flow patterns, seasons, and special situations (i.e., a non-episode and a wet episode) (see table 2-27), and the agreement between predicted and oberved regional $SO_4^=$ concentrations has been good for reasonable values of the conversion and removal rates except in the vicinity of weather fronts and in areas with poor resolution in the wind field (Niemann, Hirata, and Smith, 1979). While additional model evaluation is desirable as well as model refinement to include more resolution in the vertical dimension (2 dimensional model), the model evaluation results so far are encouraging.

The SURE II gridded emission inventory (see figure 2-28) was used to provide the SO_2 emission inputs to the pseudo-spectral transport model. It is of interest to point out that nine of the eleven 80 km x 80 km grids in the SURE inventory along the Ohio River have SO_2 emissions greater than

Table 2-27. Status of ORBES Regional Transport (Prahm) Model Evaluation

Episode Number	Sulfate Data Day	Weather Pattern	MH[a]	Input Parameters		
				d[b]	d_1[c]	d_2[d]
1	6/11/76	high pressure with Atlantic low	1400-2500	1	1	0.1
2	1/24/75	sub-synoptic high	600	0.7	1	0.1
3	6/23/75	high pressure with surrounding fronts	1300-1700	1	1	0.1
4	8/27/74	high pressure with occluding front	700-1600	1	1	0.1
5	7/10/74	high pressure with stationary front	1100-2000	1	1	0.1

[a] mixing height in meters

[b] conversion rate in %/hr

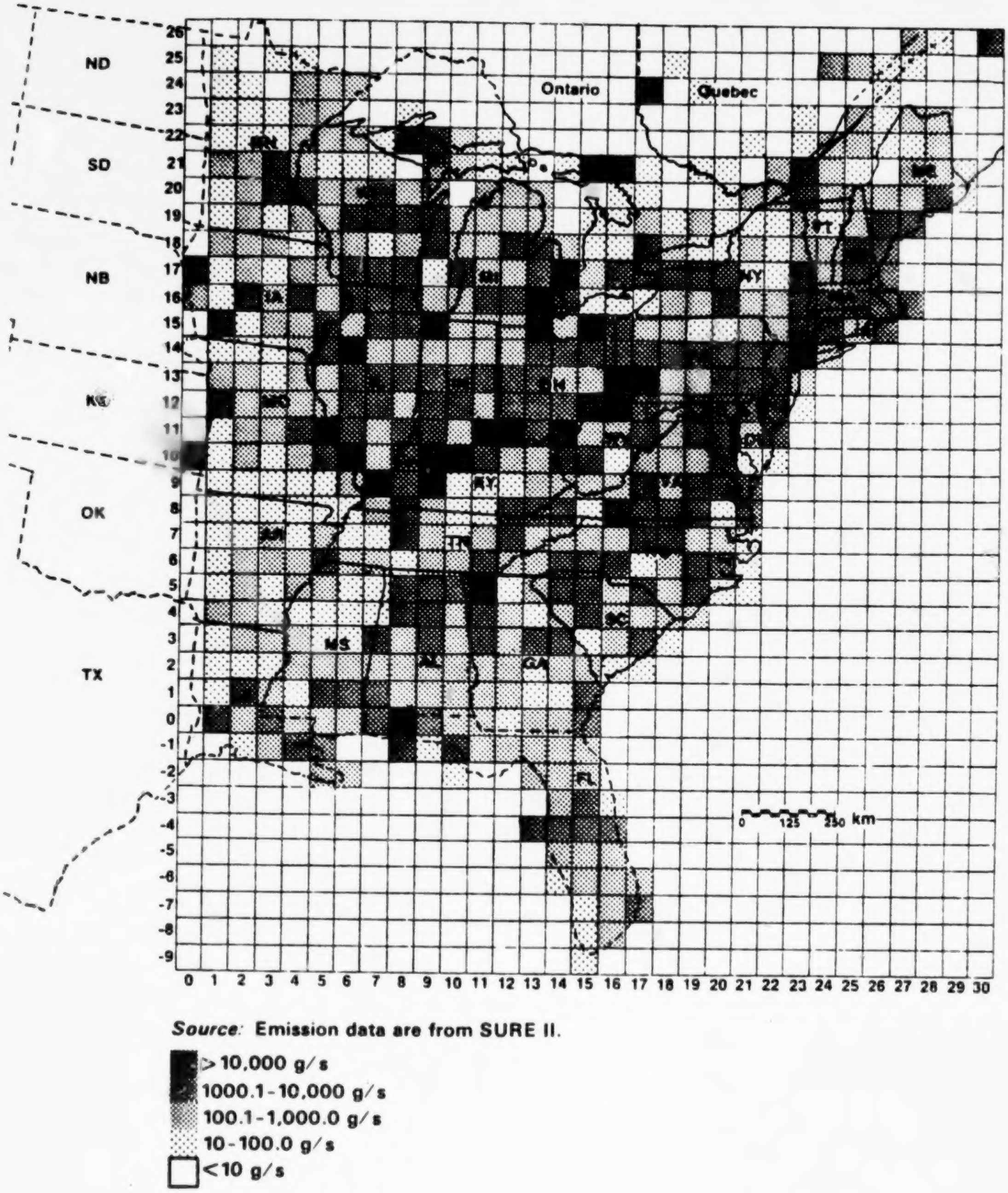
[c] SO_2 dry deposition velocity (cms^{-1})

[d] SO_4 dry deposition velocity (cms^{-1})

10,000 gm/s, while most of the other grids in the ORBES region have SO_2 emissions in the range of 100 gm/s to 10,000 gm/s on an annual basis.

The wind velocity fields were prepared using twice daily observations (OOGMT and 12GMT) from 54 upper air stations in the eastern United States and Canada. The winds at 300 meters (winter season) or 600 meters (summer season) from the upper air stations were interpolated to the centers of the grid squares. A linear time interpolation was applied to the winds for each time step in the numerical integration of the transport equations. The twice daily mixing heights were available from five stations in the midwest to provide a time-varying (constant over the region) mixing height during the episodes to be simulated.

Five regional sulfate episodes were evaluated by the regional transport model to determine source-receptor relationships during these episodes. These five episodes were selected to provide a representative cross-section of flow patterns, seasons, and special situations. They occurred on August 27, 1974; July 10, 1974; June 11, 1976; and June 23, 1975.


ND
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TX
Ontario
Quebec
NY
VT
ME
MI
IA
MO
KY
VA
AR
TN
MS
AL
GA
SC
FL
0 125 250 km
> 10,000 g/s
1000.1 - 10,000 g/s
100.1 - 1,000.0 g/s
10 - 100.0 g/s
< 10 g/s

Source: Emission data are from SURE II.

Figure 2-28. Annual SO_2 *emission rates in the eastern U.S.*

2.6.1 August 27, 1974 Sulfate Episode

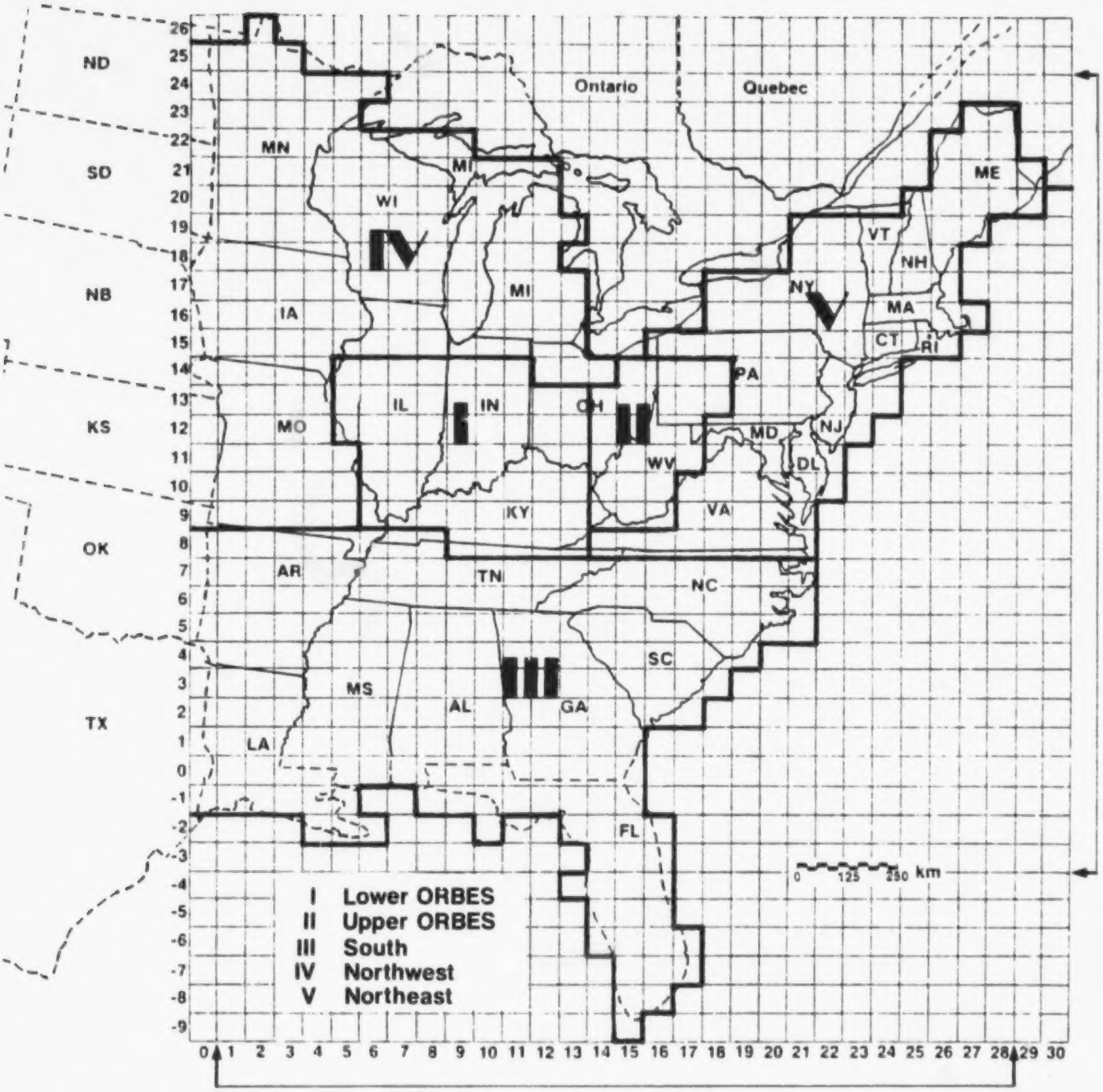
- During the August 27 sulfate episode, modeling results suggest that sulfur dioxide emissions in the lower ORBES region contributed about 75 percent of the peak sulfate concentrations in the upper region. Nearly 100 percent of the lower region's contribution came from utility emissions.

- On a state basis, the Prahm model predicts that, during the August 27 episode, utility sulfur dioxide emissions from the ORBES states of Illinois, Indiana, and Kentucky produced peak sulfate concentrations of the order of 8, 14, and 25 micrograms per cubic meter, respectively, at locations in the upper ORBES region.

The most frequent type of sulfate episode according to the analysis of sulfate data from 1974-1977 is evidenced by the August 27, 1974, sulfate episode. This type of episode involves a rather straightforward, simple flow pattern of extremely persistent winds from west to east over the ORBES region for several days. During such an episode, the transport of emissions, particularly utility emissions, from the lower part of the region appears to have a significant impact on concentrations in the upper part of the region.

The ORBES regional transport model was run for the August 25-29, 1974, period for the entire eastern U.S. and for the 5 subregions (see figure 2-29). In addition, since the existing emission sources are regulated on a state basis under the State Implementation Plans (SIPs), this episode also was run for the 6 ORBES states. Fortunately, the boundaries of most of the eastern states can be approximated to a high degree by the SURE emission inventory grid except in the Ohio-Pennsylvania-West Virginia border area where a higher resolution grid probably is needed for the evaluation of the impacts of individual sources in those three states on one another.

The calculated SO_2 concentrations show a connected region of elevated regional concentrations extending all the way from the lower to the upper ORBES region during August 26-29, 1974. The source intensification effect from extremely persistent winds blowing over the high SO_x emission grids along the Ohio River and downwind of Allegheny County is apparent in the predicted SO_2 concentrations on August 27, 1974 (see figure 2-30). The predicted $SO_4^=$ concentrations also show a connected region of elevated concentrations from the lower to upper Ohio River region on August 26, 1974, and then an intensification of the concentrations and transport to the northeast of the upper Ohio River region on August 27, 1974 (see figure 2-31). After August 27, 1974, the predicted $SO_4^=$ concentrations show a disorganized pattern due to the passage of a strong cold front over most of the northeastern U.S. The agreement between the predicted and observed $SO_4^=$ concentrations is good in the upper Ohio River and northeastern subregions, but no so good in the lower Ohio River subregion. In that region the predicted maximum $SO_4^=$ concentration is close to the observed maximum concentration, but the location is probably off because of the lack of sufficient resolution in the wind


ND
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IL
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OH
PA
KY
WV
MD
DL
NJ
VA
NC
TN
AR
MS
AL
GA
SC
LA
FL
NY
VT
NH
MA
CT
RI
ME
Ontario
Quebec
I
II
III
IV
V
I Lower ORBES
II Upper ORBES
III South
IV Northwest
V Northeast
0 125 250 km
26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8 -9
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

Note: Dashed lines show extrapolated state boundaries outside the SURE study region.

Figure 2-29. Boundaries of subregions considered in the ORBES regional transport (Prahm) model.

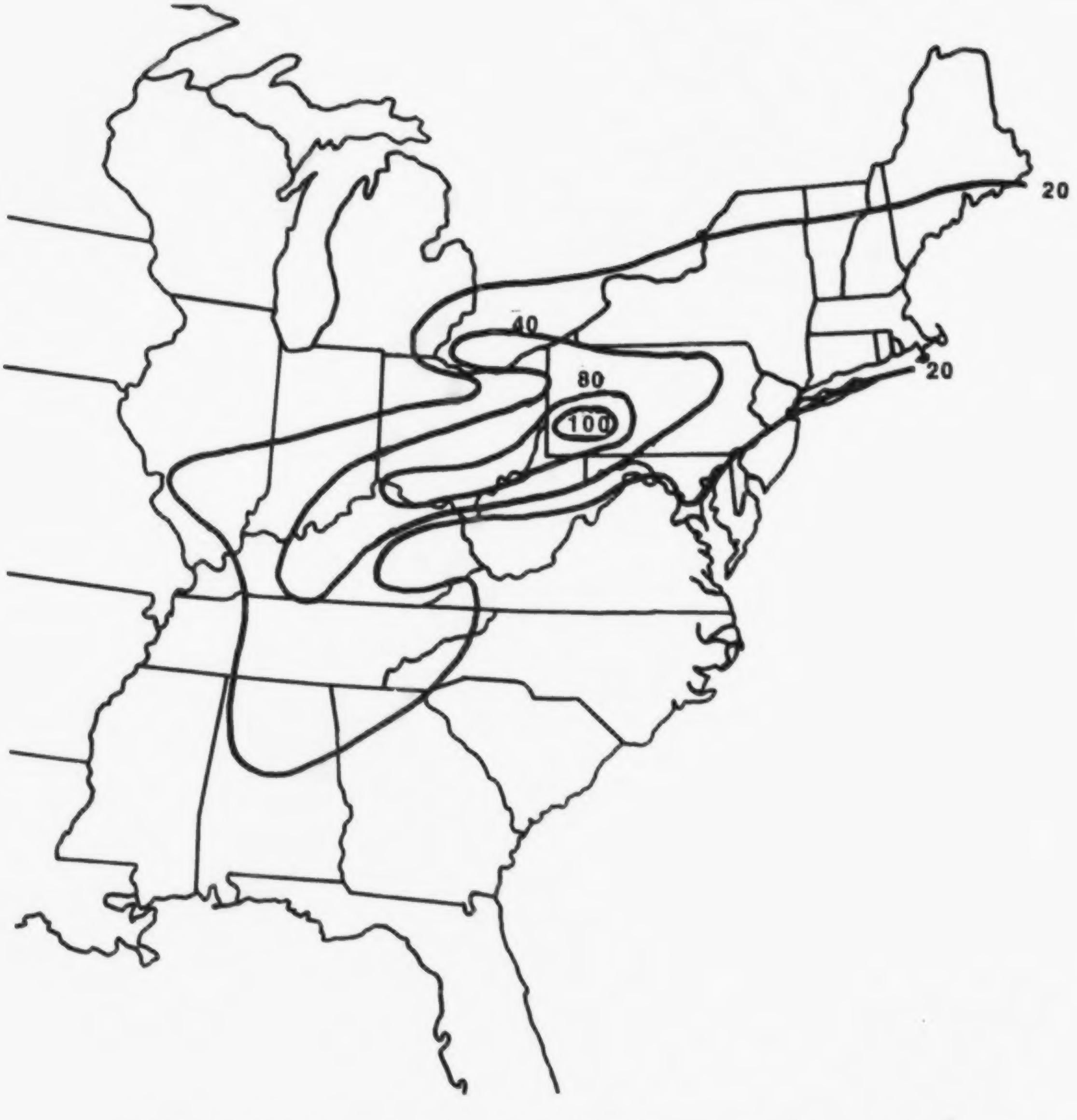

Figure 2-30. Calculated sulfur dioxide concentrations ($\mu g/m^3$) on 27 August 1974 contributed by all SO_2 emission sources.

field due to the large spacing between upper air stations in this region (i.e. Salem, IL to Dayton, OH). In fact, the meteorological tower data on this day in the lower Ohio River show extremely persistent winds more from the southerly than the southwesterly direction. If this meteorological tower data were used to supplement the upper air data on this day, the predicted maximum $SO_4^=$ concentration probably would be closer to its measured location. The parameters used in the regional transport model to simulate this episode

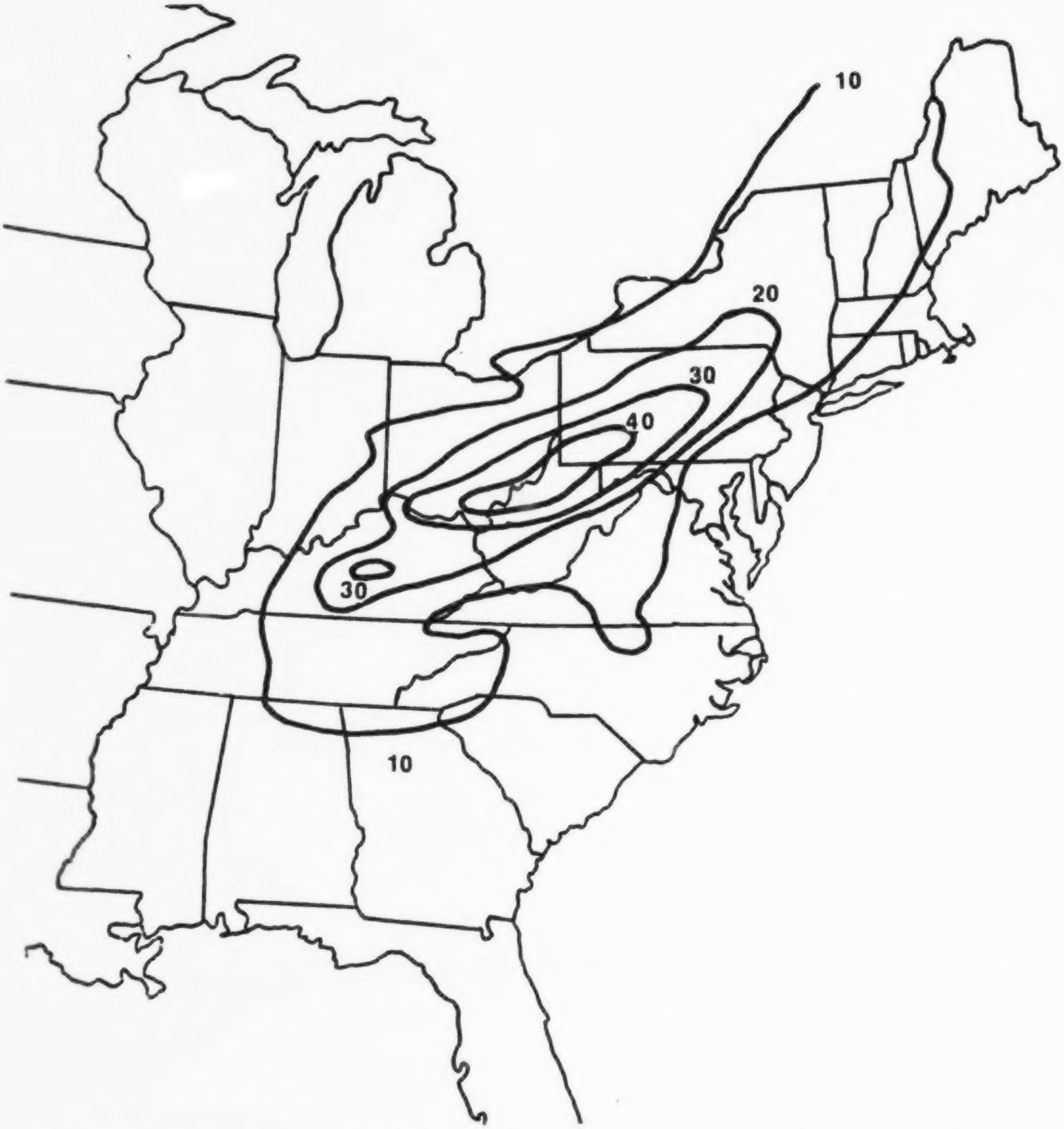

Figure 2-31. Calculated sulfate concentrations ($\mu g/m^3$) on 27 August 1974 contributed by all SO_2 emission sources.

were the same values used for the other summer episode simulations. The measured mixing heights during August 25-29, 1974, generally varied between 700 meters and 1600 meters at the Midwest stations, with the minimum value occurring on August 27 when the episode peaked over the northeastern U.S.

The calculated $SO_4^=$ concentrations on August 27 from all SO_2 emissions in the lower Ohio River subregion (not shown) and from just utility SO_2 emissions in the lower Ohio River subregion (see figure 2-32) are both quite

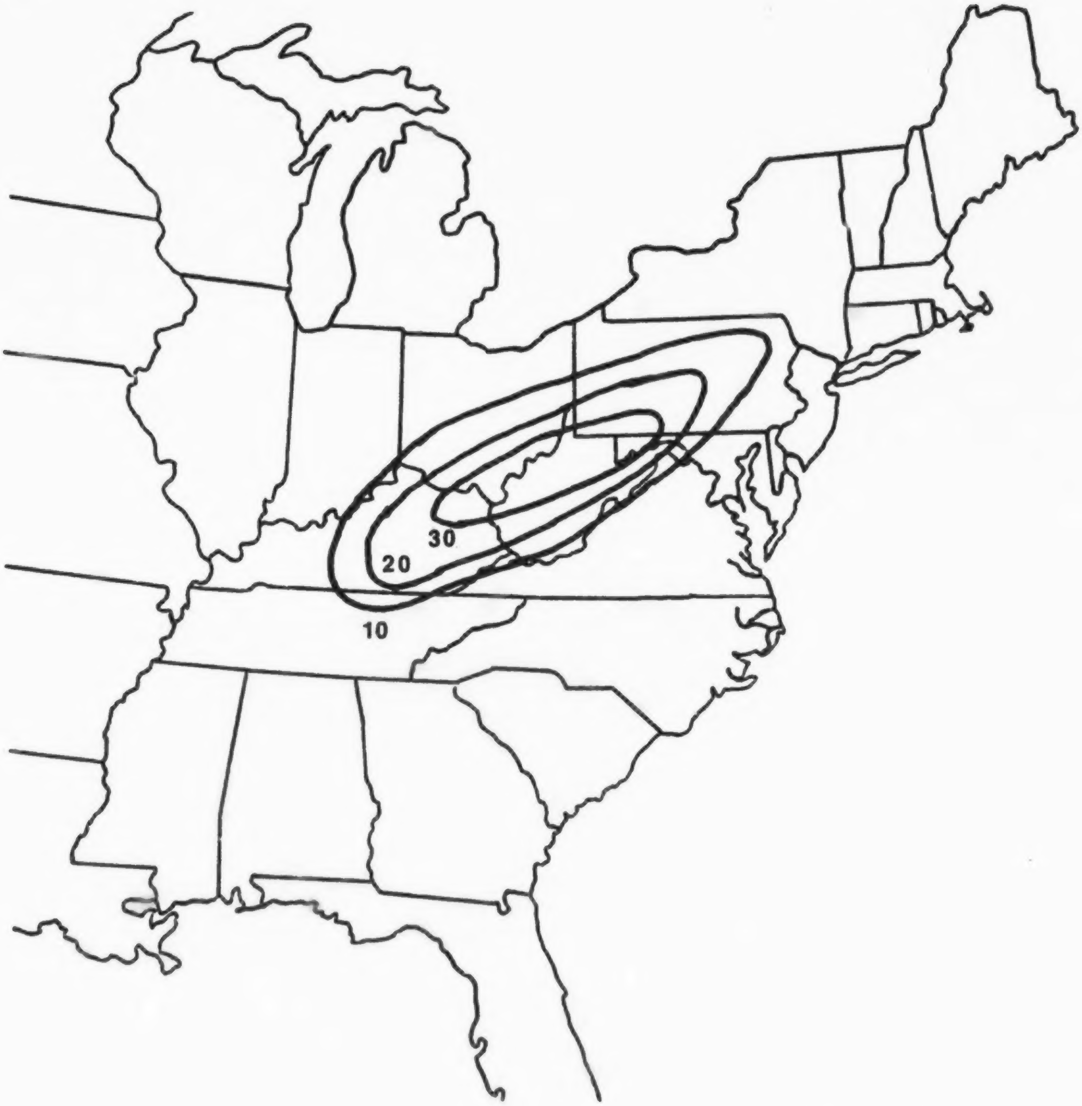

Figure 2-32. Calculated sulfate concentrations ($\mu g/m^3$) on 27 August 1974 contributed by utility sources in the lower ORBES subregion.

similar in pattern to those predicted from all SO_2 emissions in all the subregions (recall figure 2-31). In fact the regional transport model predicts that the SO_2 emissions in the lower Ohio River subregion can contribute between 75 and 90% of the peak $SO_4^=$ concentrations that are predicted to occur in the upper Ohio River subregion because of SO_2 emissions in all subregions. The model also predicts that utility SO_2 emissions contribute nearly 100% of the $SO_4^=$ concentrations that are predicted to occur in the upper Ohio River subregion because of SO_2 emissions from all source categories in the lower Ohio River subregion. These results can be attributed primarily to the presence of extremely persistent winds along the river valley during the August 27, 1974, episode since the $SO_4^=$ contributions from utility SO_2 emissions in the lower Ohio River subregion generally have been less in the other episodes with less persistent, even recirculating, winds.

On the state basis, the regional transport model predicts that SO_2 emissions in the states of Illinois, Indiana, and Kentucky produced $SO_4^=$ concentrations of about 8 $\mu g/m^3$, 14 $\mu g/m^3$, and 25 $\mu g/m^3$, respectively, in the upper Ohio River subregion during the August 27, 1974, episode. The calculated $SO_4^=$ concentrations on August 27 due to all SO_2 emissions in the Kentucky state area (see figure 2-33) show a pattern that is quite similar to those shown previously (recall figures 31 and 32) for SO_2 emissions from much larger regions.

2.6.2 Other Sulfate Episodes

- Although the three other episodes had meteorological patterns different from the August 27 episode and from each other, the Prahm model indicates that the transport of emissions again was an important factor in the concentrations recorded during all three of these episodes. During these three episodes, as in the August 27 episode, sulfur dioxide emissions from all sources in the lower region contributed significantly (as much as 80 percent) to the sulfate concentrations in the upper region. Similarly, utility sulfur dioxide emissions in the lower region alone contributed at least half (and in one episode almost all) of the sulfate concentrations in the upper region. Modeling of the June 23, 1975, episode in particular points to the importance of transport by predicting that utility sulfur dioxide emissions from the upper portion of the ORBES region contributed about 50 percent of the predicted sulfate concentrations in an area northeast of the region. Even under nonepisodic conditions, however, these emissions would have been transported beyond the region and would have contributed to sulfate concentrations beyond the continental United States.

2.6.2.1 June 8-13, 1976, Sulfate Episode

One of the major and more complicated regional sulfate episodes reported during the 1974-1978 period occurred on June 11, 1976. The airport visibility data show that the June 11, 1976, sulfate episode was actually just one day of a persistent elevated pollution episode during June 8-13, 1976. This episode "exploded" over most of the eastern U.S. within a few days because of the recirculating flow over high emission density areas and, apparently, the pronounced warm air advection at the 500 mb level, which accelerated the conversion of SO_2 to sulfate. For the June 8-13, 1976, episode, a build-up in the calculated sulfur dioxide concentrations occurs over the high SO_2 emission grids in the ORBES region under the influence of

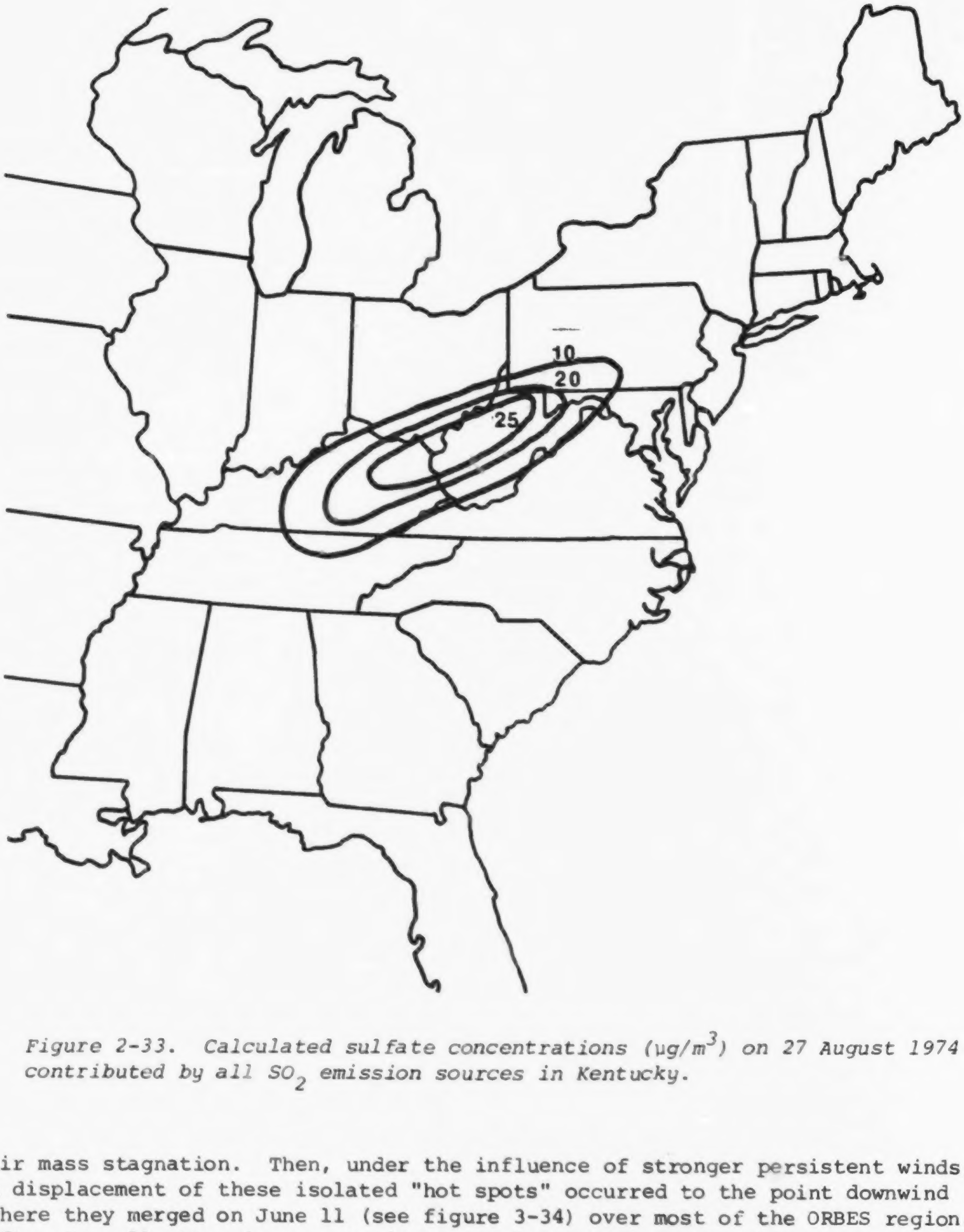

Figure 2-33. Calculated sulfate concentrations (µg/m^3) on 27 August 1974 contributed by all SO_2 emission sources in Kentucky.

air mass stagnation. Then, under the influence of stronger persistent winds, a displacement of these isolated "hot spots" occurred to the point downwind where they merged on June 11 (see figure 3-34) over most of the ORBES region. After June 11, the air mass trajectories leaving the upper Ohio River region curl around over the Atlantic coast and head back towards the upper Ohio River region. This recirculating flow over the high SO_x emission area causes the predicted SO_2 concentrations to reach a peak (about 70 µg/m^3) over the

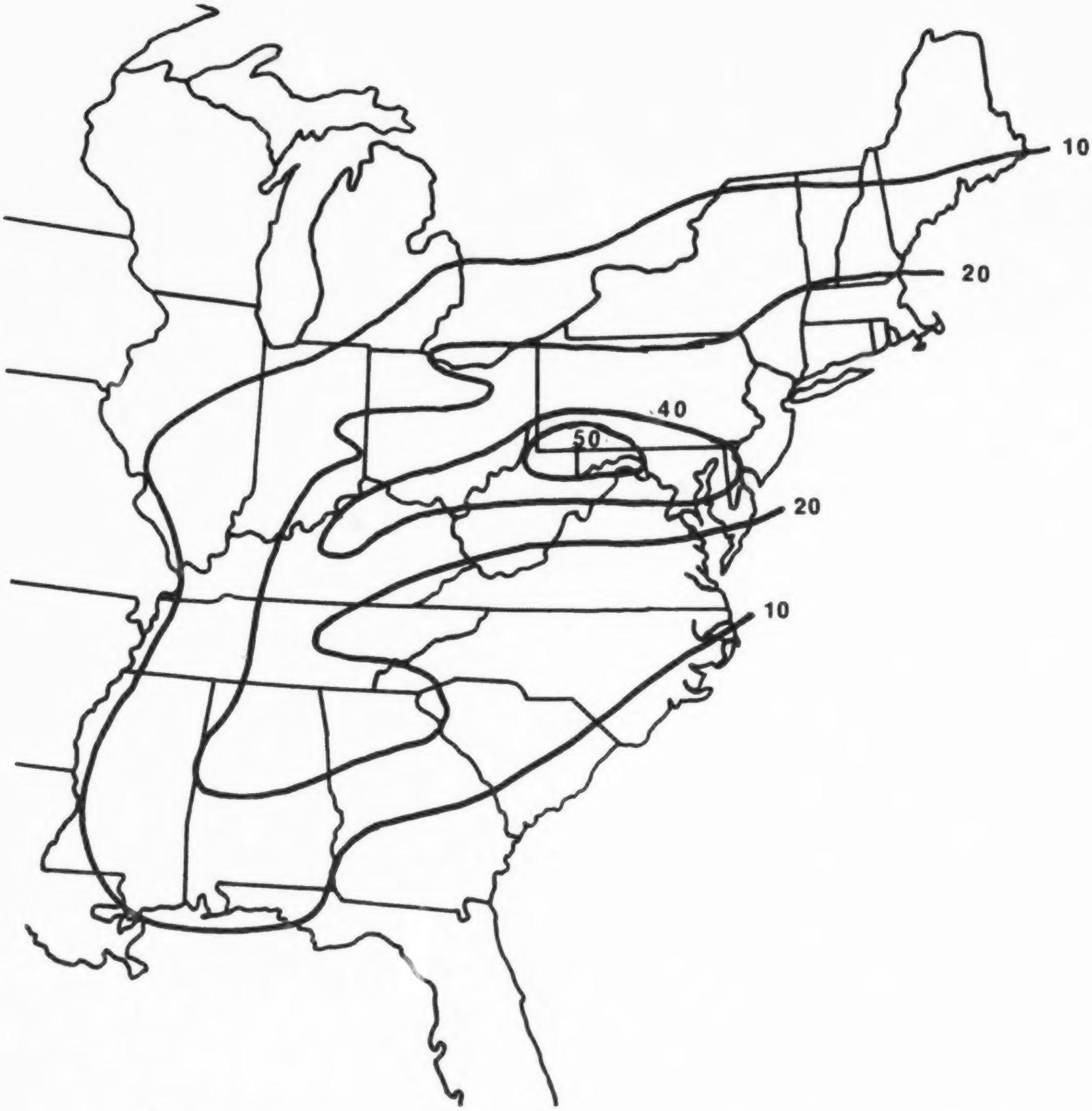

Figure 2-34. Calculated sulfur dioxide concentrations ($\mu g/m^3$) *on 11 June 1976.*

southwestern Pennsylvania border on June 12-13, 1976. After June 13, the weather pattern responsible for the recirculating air flow breaks down and the elevated regional SO_2 concentrations are dissipated rapidly. The predicted temporal variations in SO_2 concentrations are generally consistent with those observed in the AEP monitoring data, while the actual estimated magnitudes are usually less than the measured values since the latter include the influence of local as well as regional sources.

The calculated sulfate concentrations during the June 8-13, 1976, period are first built-up in areas that are rather isolated from one another and that are displaced from the areas of SO_2 build-up; the concentrations then rapidly fill in the lower $SO_4^=$ concentration areas until almost the entire southeastern U.S. is covered by $SO_4^=$ concentrations of 30 $\mu g/m^3$ or greater on June 11, 1976 (see figure 3-35). The predicted regional $SO_4^=$ concentrations on June 11, 1975 ranged from about 30-50 $\mu g/m^3$ in the upper Ohio River region and are in general agreement with the observed levels (see figure 3-35). After June 11 the predicted $SO_4^=$ concentrations peaked (about 60 $\mu g/m^3$) over the southeastern U.S. on June 13 due to the curl around in air mass trajectories; the predicted $SO_4^=$ concentrations then dissipated. Actually, the elevated $SO_4^=$ concentrations over the upper Ohio River region and the northeastern U.S. continued until about June 17 according to the air mass trajectory and sulfate data. The predicted SO_4 concentrations do show the beginning of a resurge of elevated $SO_4^=$ concentrations in the upper Ohio River region as persistent southwesterly winds drew the air mass originally over the southeastern U.S. back to the northeast. Unfortunately, this major sulfate episode occurred between the EPA/NADB sampling days (June 6 & 17), so only very limited data are available for model evaluation, namely, the TVA sulfate data on June 10, and the June 11 data from states sampling every 6 days, such as Arkansas, Ohio, Pennsylvania, and New York. However, the contours of the noontime visual range for relative humidities less than 70% at airports in the eastern U.S. show generally good agreement between the areas with visibilities less than about 6 miles and the areas predicted to have $SO_4^=$ concentrations greater than about 30 $\mu g/m^3$ during the June 8-13, 1976, period (c.f. Niemann, 1979). The parameters used in the Prahm model for the June 11, 1976, episode are reasonable values. The daily mixing heights (assumed to be the same over the entire eastern U.S.) used in the model ranged from 1400m to 2700m and generally declined from a high of 2700m on June 9 to a low of 1400m on June 12 and then increased at the end of the episode.

Because the June 11, 1976, sulfate episode covered such a large part of the eastern U.S., it is of interest to see the regional concentrations predicted from primary sulfate and total emitted particle (TEP) emissions in the SURE II inventory. The calculated primary $SO_4^=$ concentrations on June 11, 1976 (see figure 3-36) were generally 2 $\mu g/m^3$ or less over the eastern U.S., which is small compared to the $SO_4^=$ concentrations (about 40-60 $\mu g/m^3$) predicted to occur because of the chemical transformation of SO_2 emissions. On the other hand, the calculated TEP concentrations on June 11, 1976 show about the same concentrations and regional pattern as the predicted $SO_4^=$ concentrations. The predicted TEP and secondary $SO_4^=$ concentrations represent a significant transport contribution (about 100 $\mu g/m^3$) to local TSP concentrations. Some confirmation of these predictions is available from the AEP TSP data, which show that 60 of the 64 monitoring sites had TSP concentrations greater than 100 $\mu g/m^3$ on June 11 and 12, 1976. The EPA NADB data generally show TSP concentrations greater than 150 $\mu g/m^3$ (the secondary NAAQS) and $SO_4^=$/TSP ratios of 15-30% in the urban areas of the Ohio River region. The extreme concentrations occured in the industrialized areas of the upper Ohio River region where TSP concentrations in excess of 260 $\mu g/m^3$ (the primary NAAQS) were measured on 3 consecutive days in Steubenville, Ohio, around June 11, 1976.

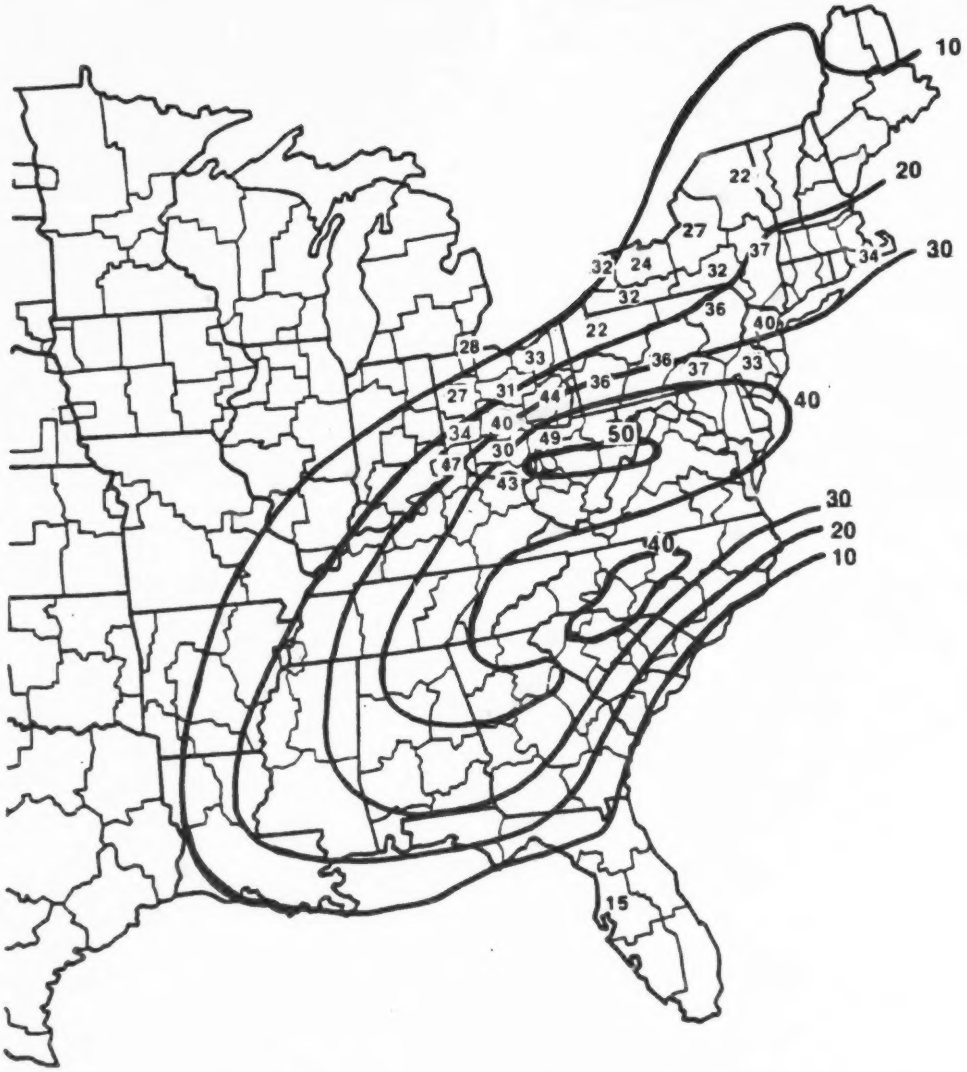
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Figure 2-35. Calculated and observed sulfate concentrations (µg/m^3) on 11 June 1976.

Since the sequence of calculated SO_2 concentrations during June 8-13, 1976, demonstrates the transport of SO_2 from the lower Ohio River to the upper Ohio River region, it is of interest to use the model to isolate the contribution of just SO_2 emissions in the lower Ohio River subregion to the entire eastern U.S. In addition, since the previous analysis of source-receptor relationships has shown that utility plants are the predominant source in many of the AQCRs in the lower Ohio River subregion, it is of interest to see the contribution of utility SO_2 emissions in the lower Ohio River subregion to the entire eastern U.S. The calculated sulfate concentra-

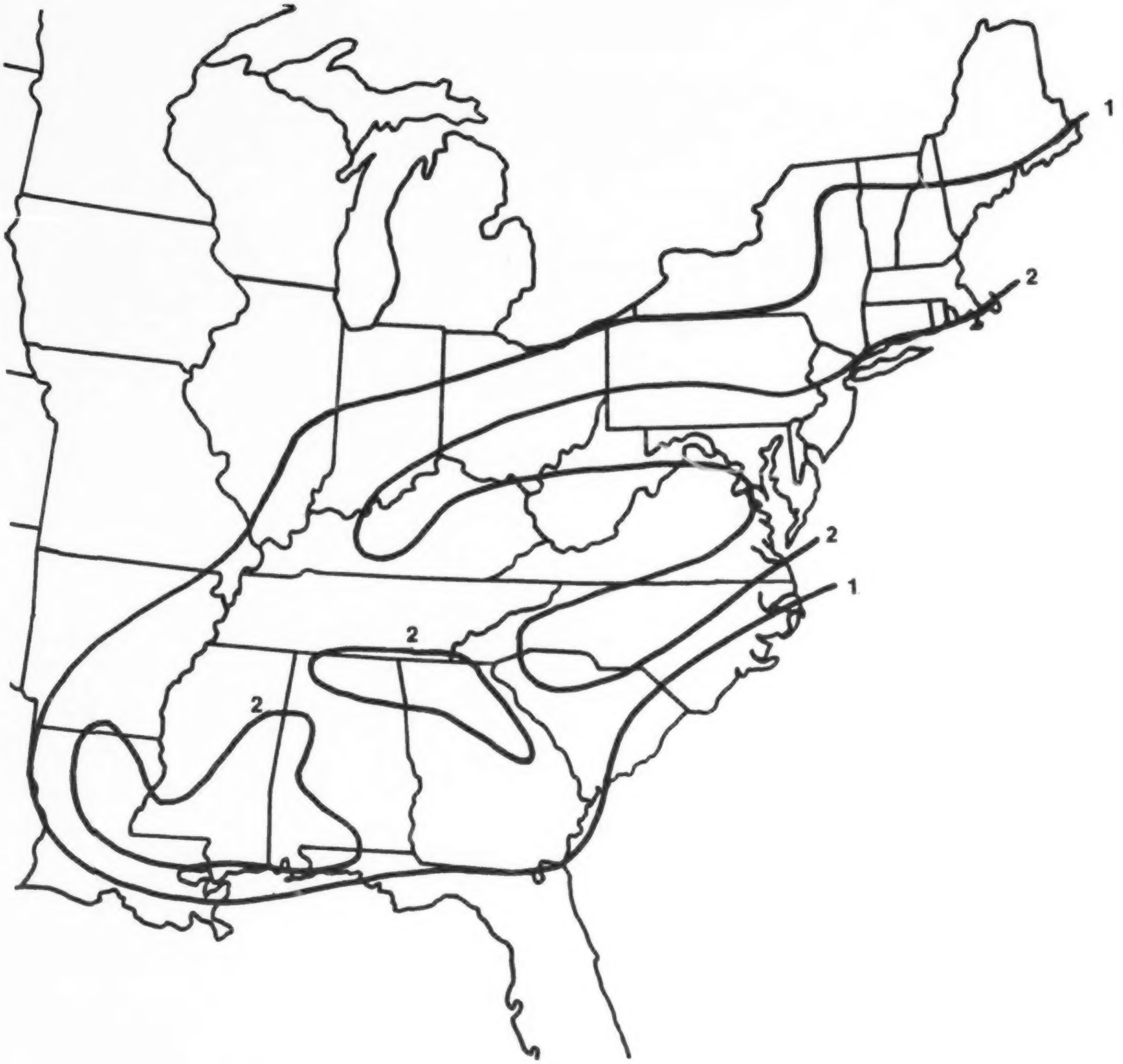

Figure 2-36. Calculated primary sulfate concentrations ($\mu g/m^3$) on 11 June 1976.

tions on June 11, 1976, from all sources and from just utility plants in the lower Ohio River subregion (see figures 3-37 and 3-38, respectively) are generally similar in pattern and just slightly less in magnitude than the sulfate concentrations predicted from all the subregions and source categories in the eastern U.S. Specifically, the regional transport model predicts that on June 11, 1976, SO_2 sources in the lower Ohio River subregion contributed about 80% of the sulfate concentrations predicted to occur in the upper Ohio River subregion from the emissions in all the subregions, while utility emissions in the lower Ohio River subregion contributed about 90%

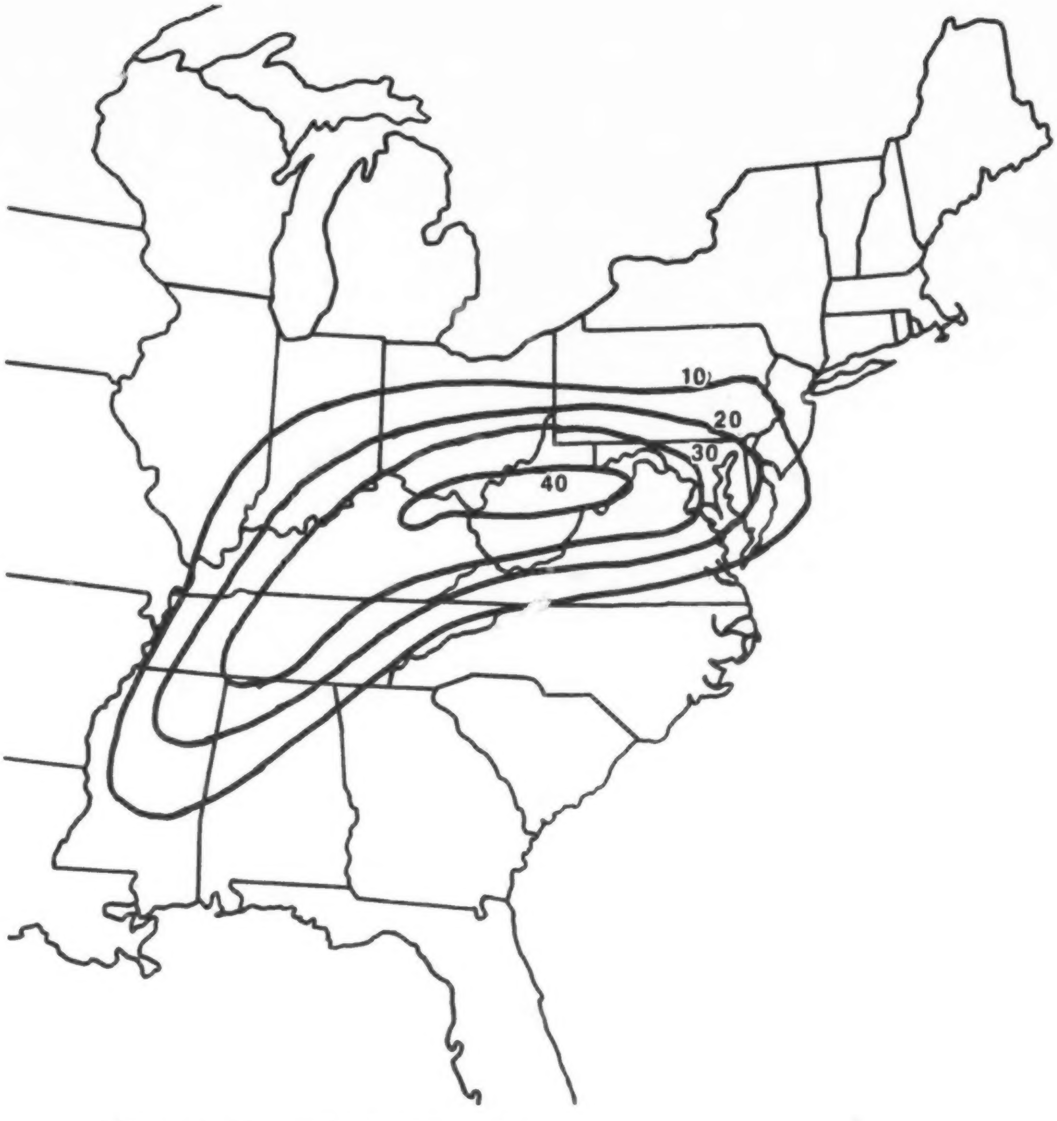

Figure 2-37. Calculated sulfate concentrations ($\mu g/m^3$) on 11 June 1976, including concentrations contributed by all emission sources in the lower ORBES subregion.

of the concentrations predicted to occur from the emissions of all source categories in the lower Ohio River subregion. After that date, the SO_2 emissions in the upper Ohio River subregion also begin to make a significant contribution to that region's $SO_4^=$ concentrations because of the curl around of the air mass trajectories, which brought some of the SO_2 emissions from the upper Ohio River subregion back to the area in the form of SO_2 and $SO_4^=$ concentrations. The calculated sulfate concentrations from the various

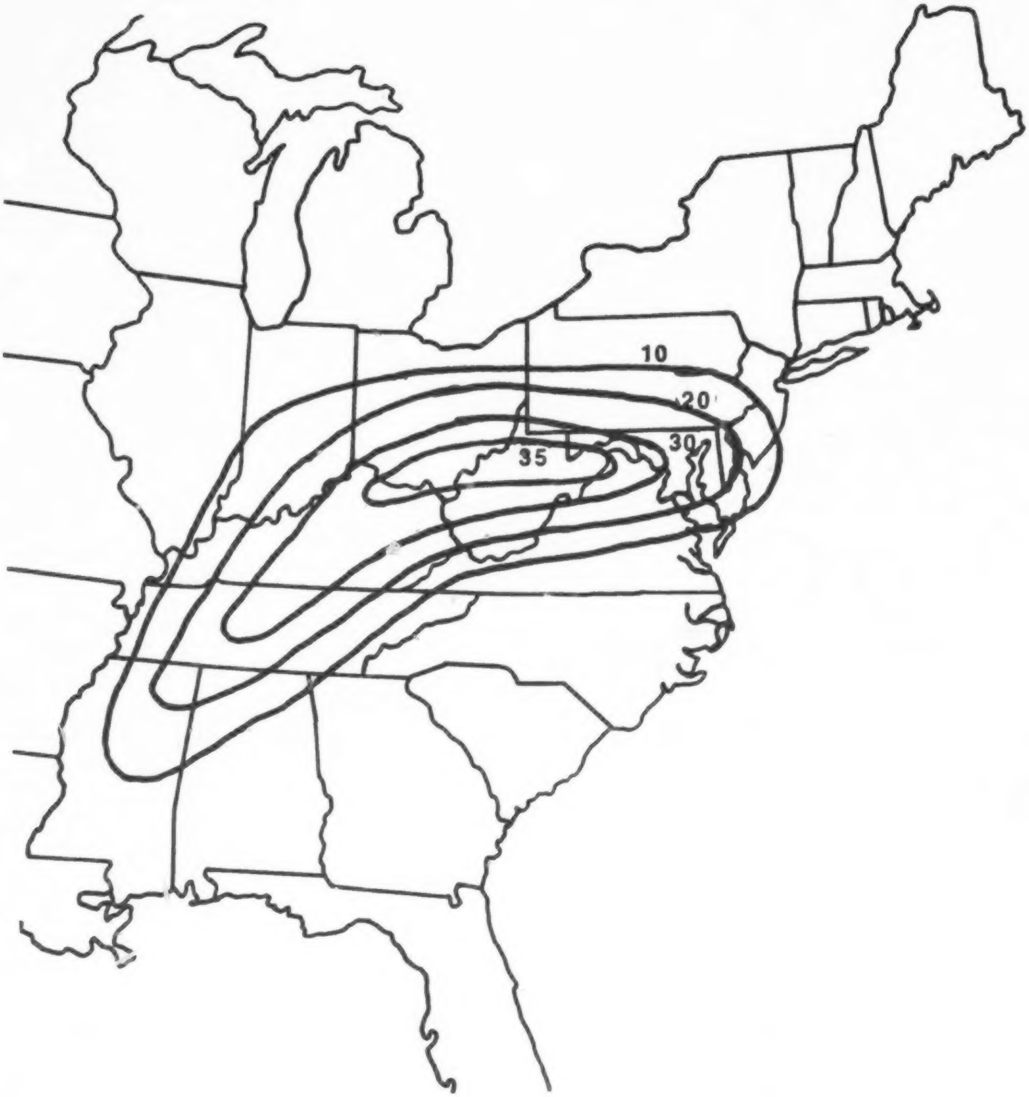

Figure 2-38. Calculated sulfate concentrations (μg/m^3) on 11 June 1976 contributed by utility SO$_2$ emissions in the lower ORBES subregion.

emission source categories in the individual subregions to the other subregions (see Table 28) are all much less than from utilities in the lower Ohio River subregion. The relative sulfate concentrations (see Table 28) are presented as ranges because of the concentration variations in the subregions.

2.6.2.2 July 7-11, 1974, Sulfate Episode

The second most frequent type of sulfate episode is exemplified by the July 7-11, 1974, episode. Such an episode includes both a stagnating high

Table 2-28. Calculated Relative Sulfate Contributions ($\mu g/m^3$) from Various Emission Source Categories in the Individual Subregions to Other Subregions (11 June 1976 Episode)

Source Category	Single Subregion Emitting Pollutants	Resulting Sulfate Contributions per Subregion				
		Lower	Upper	South	North-east	North-west
All sources	lower (I)	5-40*	10-40	5-35	5-40	5
	upper (II)	0	2	2-20	2-16	0
	south (III)	5-10	5	5-25	5	5
	northeast (V)	0	0	2-10	2-10	0
	northwest (IV)	2-4	4-6	2-16	4-8	2
Utilities alone	lower	5-35	5-35	5-30	5-35	5
	upper	0	2	2-16	2-12	0
	south	5	5	5-10	5	5
	northeast	0	0	1-3	1-5	0
	northwest	1-2	2-3	1-5	1-4	1

*denotes range in concentrations over the subregion.

pressure system that is centered over the upper region and that slowly moves southward and a quasi-stationary front along the Great Lakes. Long-range transport again plays a significant role in this kind of episode, and the emissions in particular states can contribute substantially to the sulfate concentrations in others.

On July 10, the Prahm model predicts that utility sulfur dioxide emissions from the lower portion of the ORBES region contributed about 60 percent of the sulfate concentrations in West Virginia, while utility sulfur dioxide emissions from the upper region contributed about 50 percent of the sulfate concentrations in Delaware. The model also predicts that sulfur dioxide emissions from the ORBES states of Indiana and Kentucky made the most significant contribution to the sulfate concentrations in West Virginia, on July 10, while sulfur dioxide emissions from Ohio made the most significant contribution to the sulfate concentrations in Delaware on that date.

2.6.2.3 June 23, 1975, Sulfate Episode

During the June 23, 1975, sulfate episode, there was a combination of light recirculating and strongly persistent winds. Moreover, a cold front over Nova Scotia blocked the normal westerly flow and increased the residence time of the air mass over the northeastern U.S. Because of this unusual blocking effect, the contribution of emissions from the upper ORBES region to areas northeast of the region was higher than usual. Also, because of the meteorological conditions, there was a wide variation in impacts within the region.

During the June 23 episode, utility sulfur dioxide emissions from the upper portion of the ORBES region contributed about 50 percent of the predicted sulfate concentrations northeast of the region. Under normal conditions these emissions would have been transported beyond the region and would have contributed to sulfate concentrations beyond the continental United States. Also during the June 23 episode, sulfur dioxide emissions from all source categories in the ORBES portions of Pennsylvania, Ohio and West Virginia are predicted to have contributed sulfate concentrations of 18, 12, and 7 micrograms per cubic meter, respectively, to the northeastern subregion.

In summary, the Prahm model simulations for four regional sulfate episodes are in generally good agreement with the observations, and the model is a useful screening tool for calculating the relative contributions from various source categories and source regions (including individual state areas) during the simple flow parts of episodes. The model simulations cannot be expected to provide accurate predictions in areas with active weather fronts, precipitation, and major terrain-induced mixing. Major refinements in model simulations would require improved resolution in the input wind fields and increased resolution in the vertical dimension to treat the effects of wind direction shear and emissions at different altitudes.

2.7 Annual Average Concentrations

2.7.1 Model Used to Calculate Annual Averages

The simulation of longer period SO_2 and $SO_4^=$ concentrations on a regional scale presents formidable challenges if one plans to apply a grid or trajectory type model to every day in a season or year and to a large number of emission scenarios. Even with a very computationally efficient approach like that used in the Prahm model for solving the transport equations, the amount of input data and the computer time required were beyond the scope of the ORBES project. Consequently, a simple analytical dispersion model published recently in an EPA report by Fay and Rosenzeweig (1979) was used to estimate the annual average concentrations of SO_2 and $SO_4^=$. These authors obtained simple analytical solutions to the steady state two-dimensional mass conservation equations for SO_2 and $SO_4^=$ concentrations--equations that include provisions for sinks from wet and dry deposition. These solutions are applicable as well to multiple sources of the pollutants.

Fay and Rosensweig found good agreement between SO_2 predictions from their analytical model and the numerical predictions of a plume trajectory model (NOAA/ATDL), and between $SO_4^=$ predictions from the analytical model using just power plant SO_x emissions and the area-smoothed $SO_4^=$ observations in the eastern U.S. In addition, generally good agreement was found between the $SO_4^=$ predictions of the Fay model and the Argonne ASTRAP trajectory model (Shannon, 1979), which requires large amounts of meteorological input data and trajectory calculations. These agreements suggest that for practical applications one should find an appropriate compromise between the Fay and Rosenzweig application, which used only one wind speed and direction for the entire eastern U.S., and the NOAA/ATDL and NAL/ASTRAP models, which use the highest temporal and spatial resolution available in upper air weather data.

The idea would be to apply the kind of temporal and spatial averaging to the wind data that would eliminate most of the detailed fluctuations but preserve the basic features that produce essentially the same mean transport field that one gets from a large number of trajectories. Certainly, the calculation of the seasonal and annual resultant wind vectors at all the upper air stations is the most logical first choice to try.

The Fay model was adapted by Teknekron Research, Inc. (TRI) to accept emissions and resultant winds on a grid basis--the same SURE II grid used for the episode simulations. However, it was found that the emissions and wind inputs could be less detailed than for every 80 km x 80 km grid square when the TRI/Fay model (the adapted Fay model) produced essentially the same results using the inputs on a state basis for each of the 31 states east of the Mississippi River. To be more precise, the contours of $SO_4^=$ concentrations predicted from the two different scales of emission input (grid versus state) were the same, while the contours of SO_2 concentrations contained more subregional scale details (wiggles) with the grid input than for the state input. There are insufficient valid SO_2 data to determine how real these "subregional scale wiggles" are, but even if they are real, they probably are not important in the context of a regional study.

The TRI/Fay model was evaluated against historical $SO_4^=$ data and current SO_2 and $SO_4^=$ data. For this evaluation, the emission and wind inputs on a state basis were used because the historical emissions (1960-1970) had been estimated from the Federal Energy Data System fuel consumption data, which were only available on a state basis. State level emissions and wind inputs also were used in TRI/Fay model for the SEAS total and industrial emissions, which were in the most readily usable form of the possible bases. However, the TRI USM utility emissions were available on a county basis, and these were converted to the SURE II grid.

The TRI/Fay model was applied with the same input parameters as used by Fay and Rosenzweig except for a higher annual mixing height (1000m versus 650m). The TRI/Fay model predictions for annual average SO_2 and $SO_4^=$ concentrations were found to be in generally good agreement with historical regional $SO_4^=$ patterns and with current SO_2 and $SO_4^=$ patterns. In addition, the extended Prahm model method with gridded emissions and winds also was found to produce results that were quite similar to those from the TRI/Fay model, but at a cost which was about 100 times greater. A more detailed description of the TRI/Fay model, its evaluation, and two other methods for computing annual average concentrations--namely, frequency weighting of episodes and the extended pseudo-spectral--are provided elsewhere (Niemann, 1980).

2.7.2 Annual Average Concentration Estimates

- The TRI/Fay model indicates that utility sulfur dioxide emissions in the ORBES region contribute about 75 percent of the annual regional sulfur dioxide and sulfate concentrations.

- The TRI/Fay model results also indicate that the long-range transport of utility sulfur dioxide emissions contributes about 30 percent of the observed annual sulfur dioxide concentrations in the industrialized area of the upper ORBES region.

- Of the 10 states east of the Mississippi with sulfur dioxide emissions greater than 1 million tons per year, the sulfur dioxide emissions from Ohio are predicted to contribute between 3 and 4 micrograms per cubic meter to the annual sulfate concentrations in the states of Pennsylvania, Maryland, and West Virginia. Within Ohio itself, sulfur dioxide emissions contribute over 4 micrograms per cubic meter to annual sulfate concentrations in that state.

The regional SO_2 concentrations predicted by the TRI/Fay model using 1975 EPA/NEDS total (utility plus nonutility) SO_x emissions on a state basis (see figure 2-39) show a basic symmetry about the states with the highest SO_x emissions. These concentrations also have values that are in general agreement with the SURE II (rural) measurements. The maximum predicted SO_2 concentration is about 30 $\mu g/m^3$ over Ohio.

The regional $SO_4^=$ concentrations predicted by the TRI/Fay model using 1975 EPA/NEDS total SO_x emissions on a state basis (see figure 2-40) show a symmetrical pattern that is displaced to the east of the states with the highest SO_x emissions; these concentrations also have values that are in general agreement with the isopleths of AQCR average $SO_4^=$ concentrations (NADB data) and that are somewhat higher than the SURE II measurements. The maximum predicted $SO_4^=$ concentration is about 11 $\mu g/m^3$ over the Ohio-Pennsylvania-West Virginia border.

The TRI/Fay model also can be applied to calculate the relative contribution from major source regions and categories to the entire region or to individual states as was done with the Prahm model. The regional SO_2 and $SO_4^=$ concentrations predicted by the TRI/Fay model using the 1975 EPA/NEDS SO_x emissions for utility sources only on a state basis (see figures 2-41 and 2-42) show the same basic patterns and nearly the same SO_2 and $SO_4^=$ concentration magnitudes, respectively, as those using the SO_x emissions from all sources (recall figures 2-39 and 2-40). In fact, the model predictions of the $SO_4^=$ concentrations from just utility SO_x emissions are in closer agreement to the SURE II $SO_4^=$ measurements than were the model predictions using all the SO_x emissions. At present, the significance of this is not known. It is possible that nonutility SO_x emissions actually make a smaller contribution to rural $SO_4^=$ concentrations because of their generally shorter stacks. The TRI/Fay model is not sophisticated enough to differentiate between tall stack and short stack emissions, but could be applied with different conversion and removal parameters for utility and nonutility source categories.

Comparing the two sets of results, the TRI/Fay model predicts that utility SO_2 emissions contribute about 75% of the regional annual average SO_2

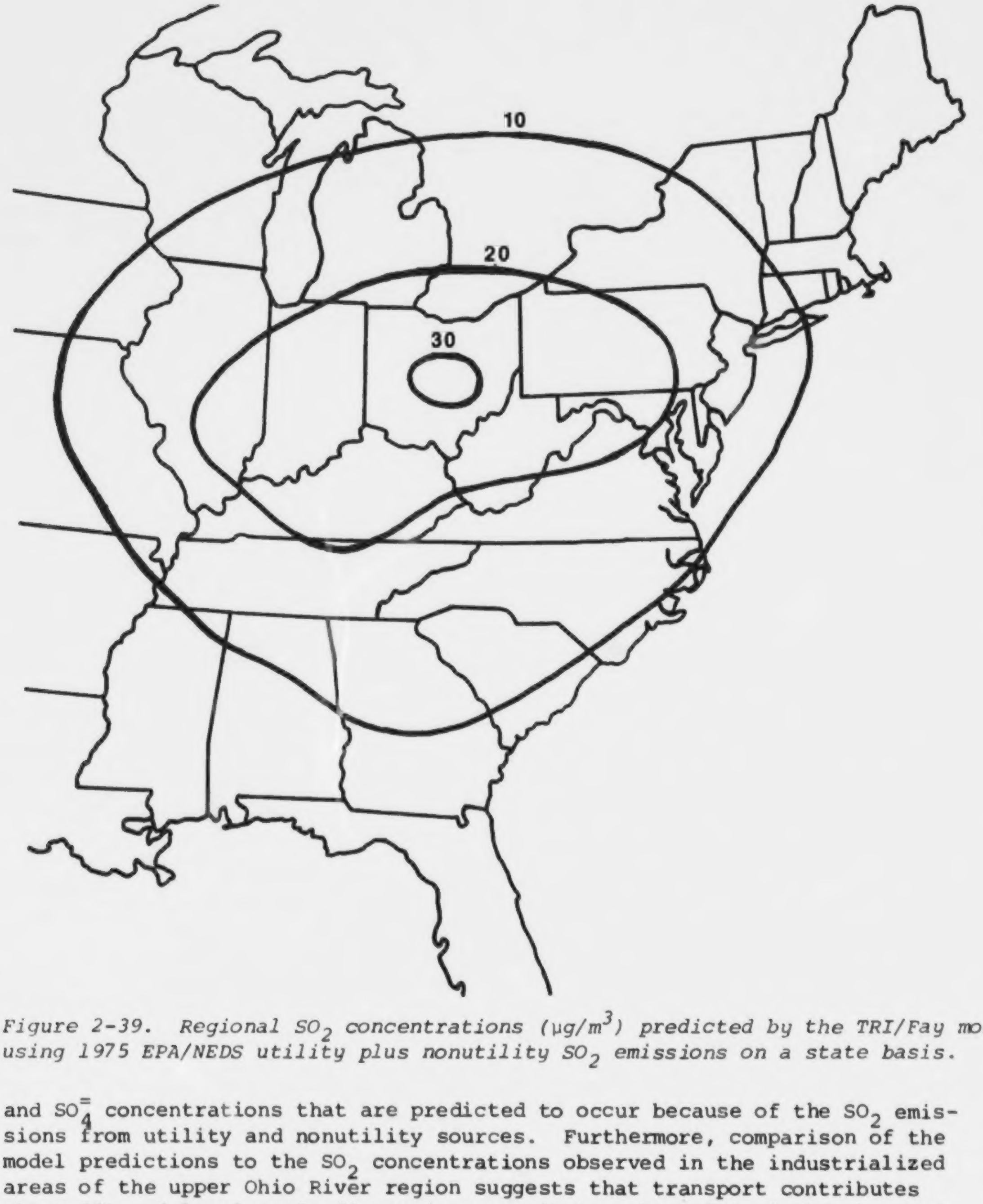

Figure 2-39. Regional SO_2 concentrations ($\mu g/m^3$) predicted by the TRI/Fay model using 1975 EPA/NEDS utility plus nonutility SO_2 emissions on a state basis.

and $SO_4^=$ concentrations that are predicted to occur because of the SO_2 emissions from utility and nonutility sources. Furthermore, comparison of the model predictions to the SO_2 concentrations observed in the industrialized areas of the upper Ohio River region suggests that transport contributes about 30% and local scale dispersion contributes about 70% of the observed annual SO_2 concentrations.

The TRI/Fay model also was applied to the SO_2 emissions from the lower Ohio River subregion states (Illinois, Indiana, and Kentucky) from the upper

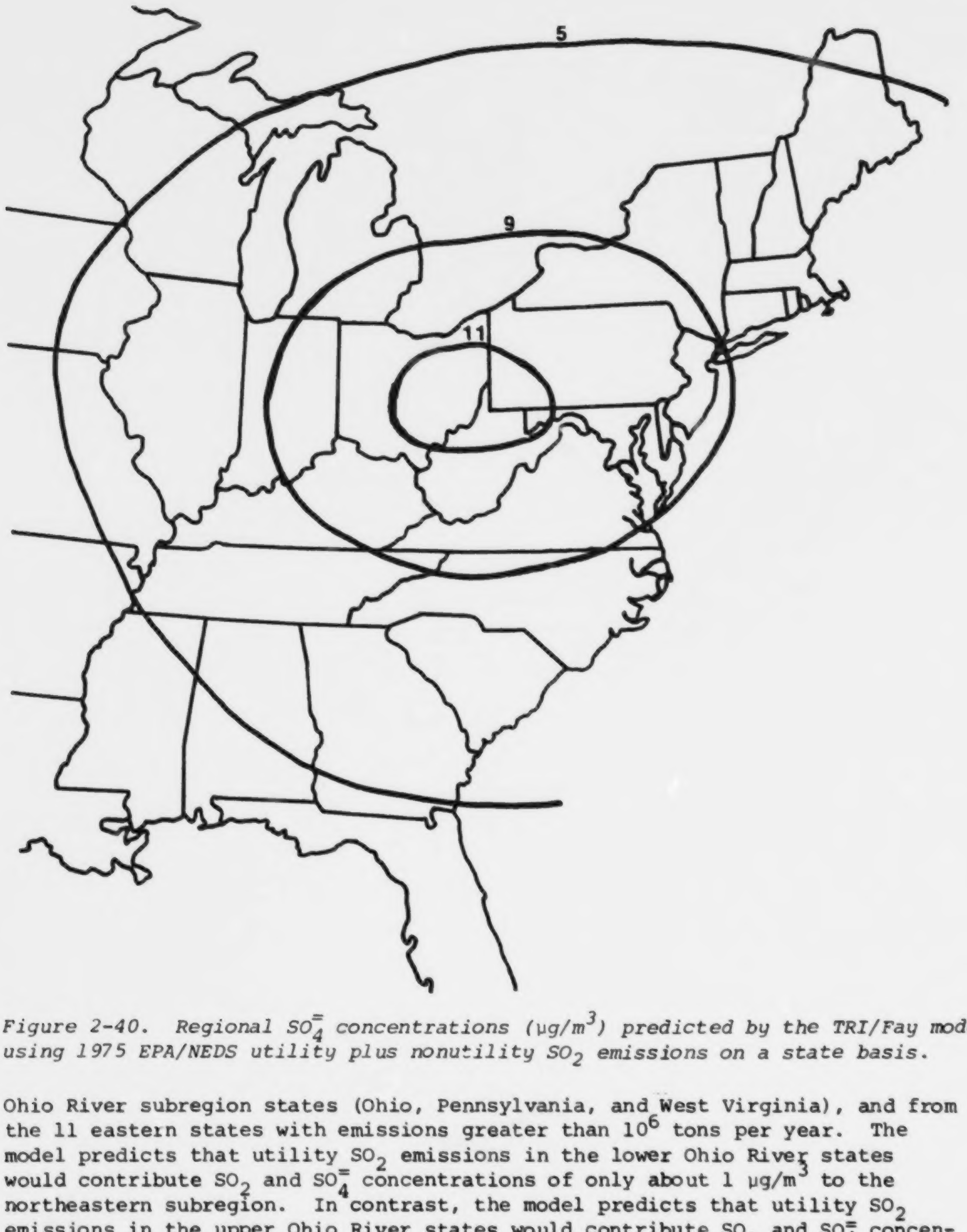

Figure 2-40. Regional $SO_4^=$ concentrations ($\mu g/m^3$) predicted by the TRI/Fay model using 1975 EPA/NEDS utility plus nonutility SO_2 emissions on a state basis.

Ohio River subregion states (Ohio, Pennsylvania, and West Virginia), and from the 11 eastern states with emissions greater than 10^6 tons per year. The model predicts that utility SO_2 emissions in the lower Ohio River states would contribute SO_2 and $SO_4^=$ concentrations of only about 1 $\mu g/m^3$ to the northeastern subregion. In contrast, the model predicts that utility SO_2 emissions in the upper Ohio River states would contribute SO_2 and $SO_4^=$ concentrations of about 3 $\mu g/m^3$ and 2 $\mu g/m^3$, respectively, to the northeastern subregion, and SO_2 and $SO_4^=$ concentrations of about 12 $\mu g/m^3$ and 3 $\mu g/m^3$, respectively, to the upper Ohio River subregion itself.

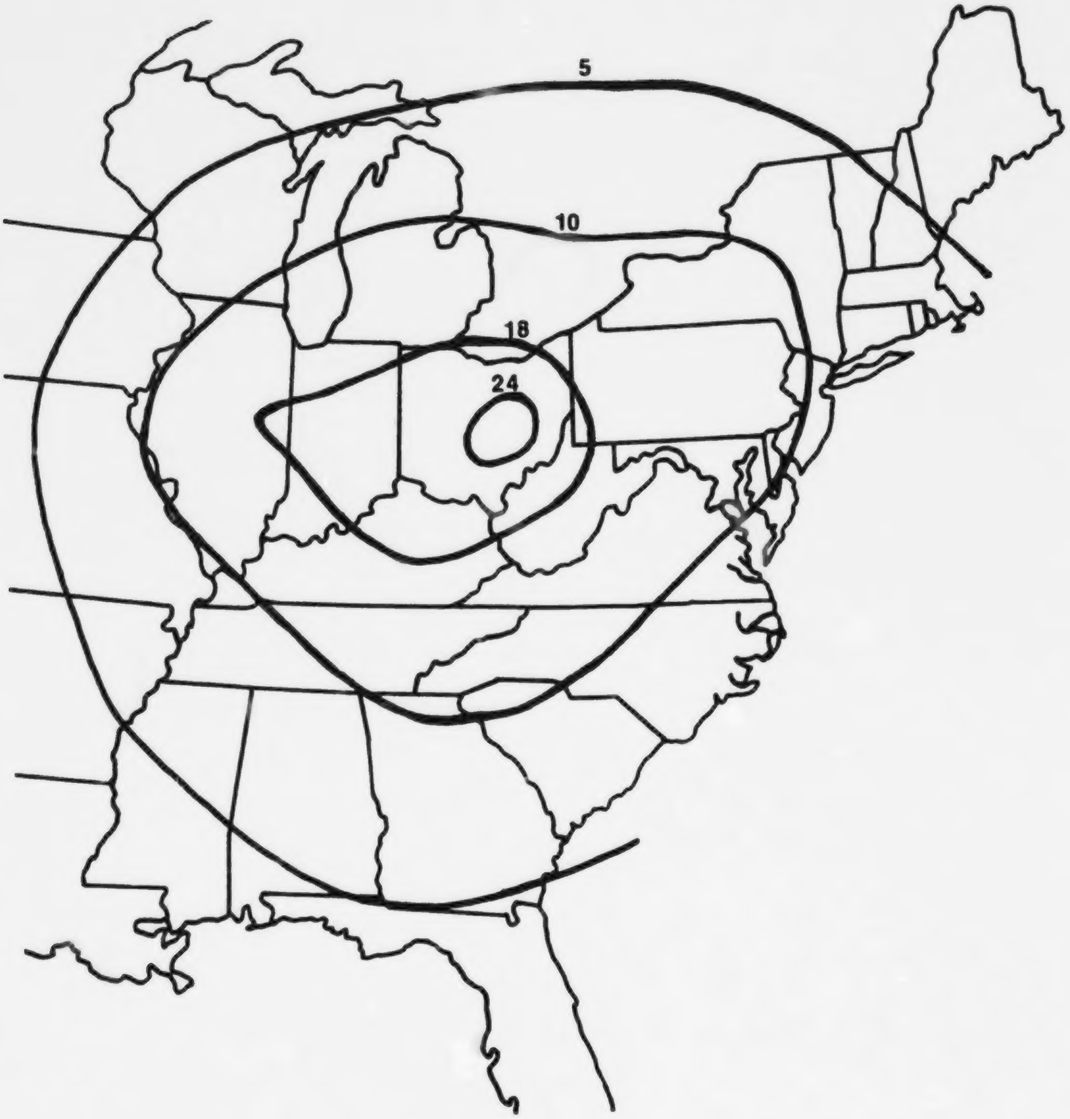

Figure 2-41. Regional SO_2 *concentrations* ($\mu g/m^3$) *predicted by the TRI/Fay model using 1975 EPA/NEDS utility* SO_2 *emissions on a state basis.*

Finally, of the 11 eastern states with total EPA/NEDS SO_2 emissions greater than 10^6 tons per year (as predicted by the model), the SO_2 emissions from Ohio have the greatest impact on the annual average $SO_4^=$ concentrations in the states of Pennsylvania (3.6 $\mu g/m^3$), Maryland (3.2 $\mu g/m^3$), and West Virginia (3.3 $\mu g/m^3$), as well as on Ohio itself (4.1 $\mu g/m^3$).

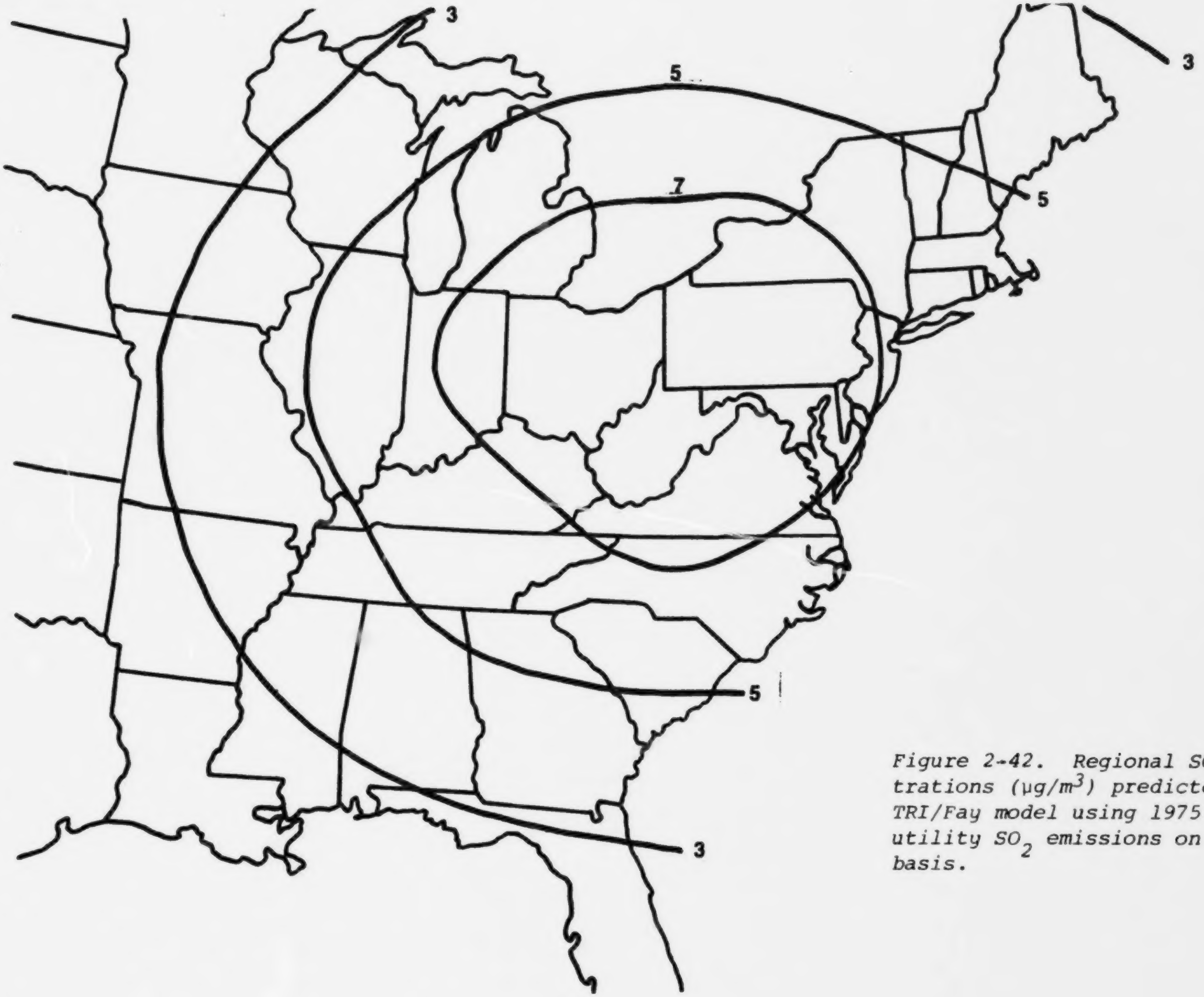

Figure 2-42. Regional $SO_4^=$ concentrations ($\mu g/m^3$) predicted by the TRI/Fay model using 1975 EPA/NEDS utility SO_2 emissions on a state basis.

2.8 Transboundary with Canada

- Utility sulfur dioxide emissions in the six ORBES states contribute about 50 percent of the annual sulfur dioxide and sulfate concentrations estimated to occur in southeastern Canada.

The Prahm model simulations and the TRI/Fay model simulations have both shown SO_2 and $SO_4^=$ impacts extending into southeastern Canada from U.S. SO_x emission sources. The Prahm model simulations have included the SO_2 emissions from Canadian sources since they have been included in the SURE II inventory. However, the Canadian Environmental Protection Agency has recently found that the Canadian SO_2 emissions in the SURE II inventory may be too low by as much as a factor of two. Time did not permit the revision of the SURE II inventory for the Canadian grids or a re-run of the Prahm model on the baseline episodes and USM emissions; however, it was possible to include the revised Canadian SO_2 emissions in the runs of the TRI/Fay model. The purpose of this section is to use the TRI/Fay model calculations to make a very preliminary assessment of the following transboundary impacts: (1) the impacts of all eastern U.S. SO_2 emissions on southeastern Canada, (2) the impacts of all southeastern Canada SO_2 emissions on the northeastern subregion in the U.S., (3) the impacts of all SO_2 sources in the ORBES states on southeastern Canada, and (4) the impacts of utility SO_2 sources in the ORBES states on southeastern Canada. In addition, the SO_2 monitoring data from special networks along the northern shore of Lake Erie were used to assess the transboundary impacts directly without resorting to model calculations.

The revised Canadian SO_2 emissions on the SURE II grid were aggregated to just 15 grid cells to simplify their input to the TRI/Fay model. This aggregation of Canadian emissions shows that the total SO_2 emission rate from sources in eastern (west of 105° west longitude) Canada is about 4.6×10^6 tons per year, which is about 30% greater than the SO_2 emissions in Ohio, the state with the largest SO_2 emission rate in the U.S., and about 25% of the total SO_2 emissions from the 11 eastern states with emissions greater than 10^6 tons per year.

The regional SO_2 and $SO_4^=$ concentrations estimated by the TRI/Fay model using the eastern Canada SO_2 emissions (see figures 2-43 and 2-44) show a general symmetry about the grid (15, 22), which has about one-third of the total SO_2 emissions in eastern Canada due to the world's largest copper smelter, namely, the INCO Sudbury Smelter. The TRI/Fay model estimates that the annual average SO_2 and $SO_4^=$ concentrations over the northeastern U.S. are only about 2 g/m^3 as a result of SO_2 emissions from eastern Canada sources. However, the model estimates that annual average SO_2 and $SO_4^=$ concentrations over southeastern Canada, near grid (20,25), are about 14 g/m^3 and 9 g/m^3, respectively (recall figures 2-39 and 2-40), because of SO_2 emissions from eastern U.S. sources. These predictions are slightly higher than the observed SO_2 and $SO_4^=$ concentrations at rural monitors in Ontario Province. The model calculations for the eastern Canada emissions were made with a mixing height of 650 meters, while the calculations for the eastern U.S. emissions were made with a mixing height of 1000 meters. The mixing height data in southeastern Canada show generally lower mixing heights than in the eastern

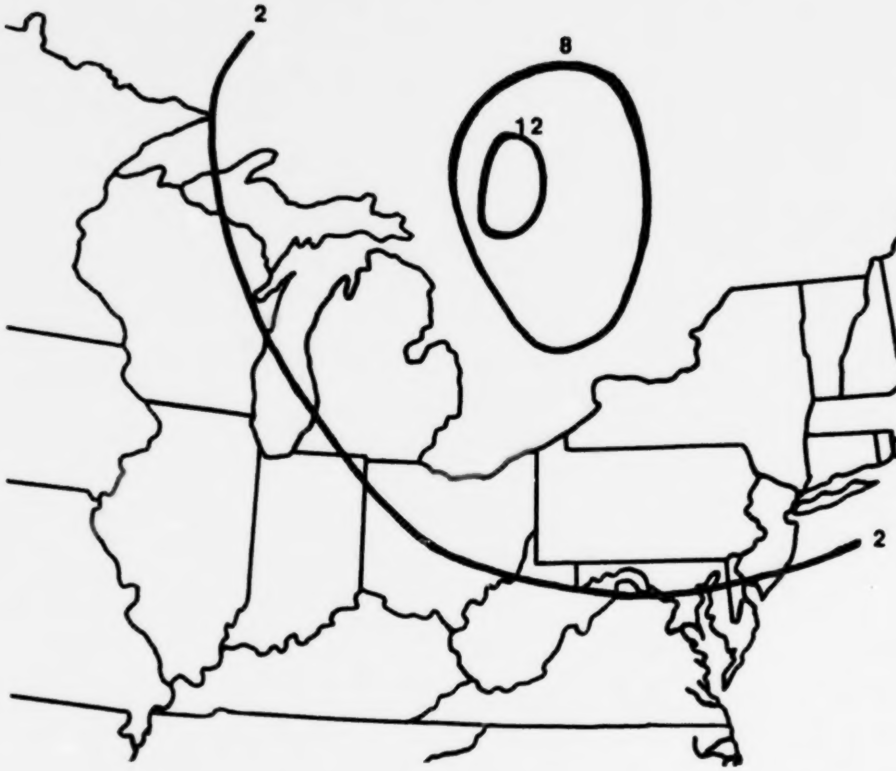

Figure 2-43. Regional SO_2 concentrations ($\mu g/m^3$) predicted by the TRI/Fay model using Canadian utility plus nonutility SO_2 emissions.

U.S., especially in the fall and winter seasons. One also could argue that a lower SO_2 and $SO_4^=$ conversion rate for the Canadian SO_2 emissions should be used because the air masses over Canada are generally colder and dryer than over the eastern U.S., a fact that would cause the estimated $SO_4^=$ concentrations to be lower and the SO_2 concentrations to be higher than those shown (recall figures 2-43 and 2-44).

The TRI/Fay model also was applied to the SO_2 emissions from just the 6 ORBES states and to just the utility SO_2 emissions in the 6 ORBES states. The model estimates that the SO_2 and $SO_4^=$ concentrations from the former emissions would be about 8 $\mu g/m^3$ and 6 $\mu g/m^3$, respectively, and that the SO_2 and $SO_4^=$ concentrations from the latter emissions would be about 6 $\mu g/m^3$ and 5 $\mu g/m^3$, respectively, in southwestern Canada in the vicinity of grid point (20,25). Thus utility SO_2 emissions in the 6 ORBES states are estimated to contribute about 50% of the SO_2 and $SO_4^=$ concentrations estimated to occur in southeastern Canada because of all eastern U.S. SO_2 emissions.

Ontario Hydro is one of the three largest utilities in eastern North America, and American Electric Power and the Tennessee Valley Authority are

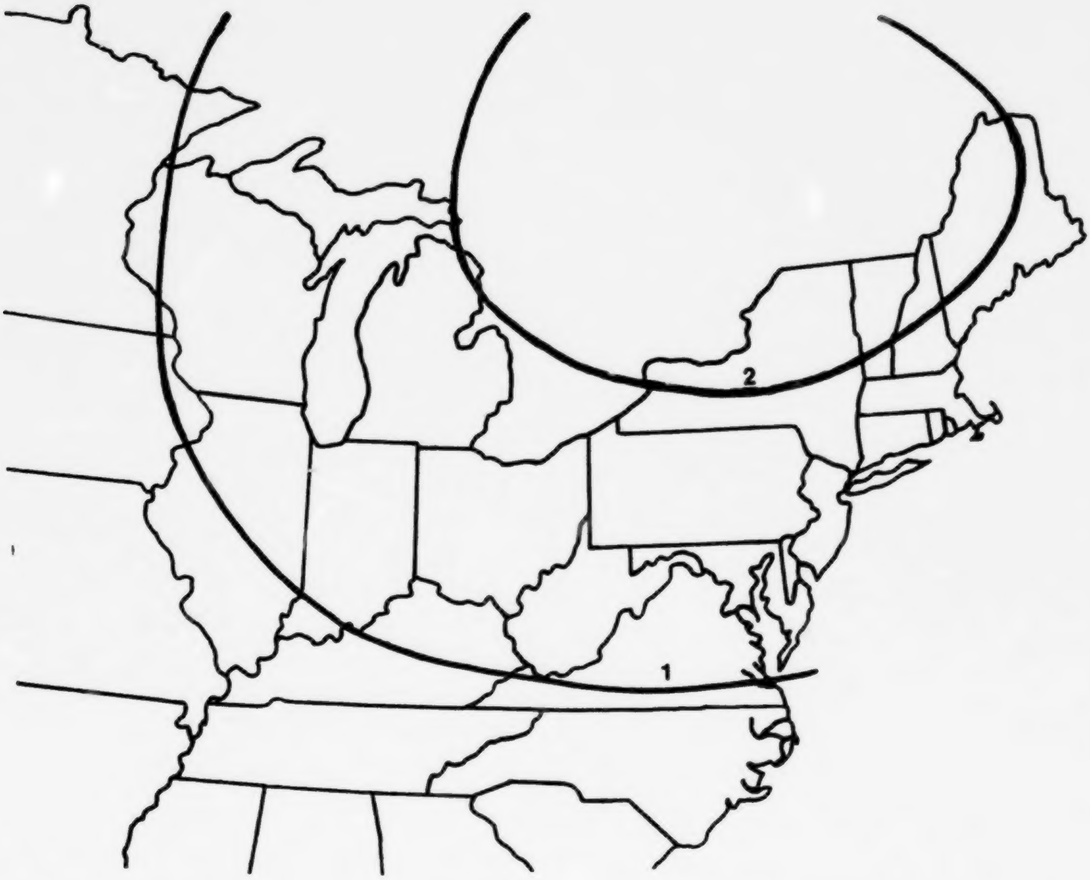

Figure 2-44. Regional $SO_4^=$ concentrations ($\mu g/m^3$) predicted by the TRI/Fay model using Canadian utility plus nonutility SO_2 emissions.

the next two largest utilities. Fortunately, Ontario Hydro is involved in air quality monitoring in the vicinity of 7 existing and 2 proposed power plant sites. The monitoring networks in the vicinity of 3 of the 7 existing plants are along the northern shore of Lake Erie and in the extreme southwestern part of Ontario Province near Lake St. Clair. The two networks near Lake St. Clair are useful for determining transboundary impacts along the Michigan-Ontario border. The Ontario Hydro monitors in the vicinity of their Nanticoke Generating Station on the north shore of Lake Erie are very useful for determining the transport of SO_2 from sources in the northeastern part of the ORBES region and from the industrialized counties along the southern shore of Lake Erie.

The 25 highest daily SO_2 concentrations in each of the 7 networks in the vicinity of the 7 existing plants have been extracted for 1976 and in the vicinity of the Nanticoke Generating Station for 1977 and 1978 as well, since the latter plant has 14 monitors. This data base shows that the highest background SO_2 concentrations occur at the Nanticoke monitors and that the number of episodes at each of the monitors has varied considerably from year to year between 1976 and 1978. For example, the monitor 15 kilometers to the north of the Nanticoke Station had 12 of the 25 highest daily SO_2 concentrations in 1977, but only 3 of the 25 highest in 1976. The most dramatic variation in the distribution of SO_2 concentrations at Nanticoke occurred in 1978 when 20 of the 25 highest concentrations occurred on just two days of the year, namely, January 23-24, 1978. A detailed analysis of this period of data (Fleming, 1979) suggests that transport of SO_2 emissions from the south were at least partially responsible. The SURE II and other data also indicate a major regional SO_2 episode occurred during this period.

The 25 highest daily SO_2 concentrations in the Ontario Hydro Nanticoke monitoring network in 1977 show that at least one-third of the episodes were associated with extremely persistent winds from the south, as measured at either the Nanticoke meteorological tower or in northern Pennsylvania or both, suggesting that transport of SO_2 emissions from the northeastern part of the ORBES region and the industrialized counties along the southern shore of Lake Erie contributed to these SO_2 episodes. Subregional scale modeling is required to determine the relative contribution of SO_2 emissions inside and outside of the ORBES region to the measured episodes. The maximum daily SO_2 concentrations measured in the Nanticoke network during 1976-1977 and associated with SO_2 transport from sources to the south were about 225 $\mu g/m^3$.

Chapter 3
SCENARIO DESCRIPTIONS

In order to assess the implication of the expansion of electrical generating units in the ORBES region, it was necessary to identify an array of possible future power plant configurations in the study region. Since it is not known what the actual electrical demand growth rates and environmental regulations will be during the 25 year period considered in the study, a number of different conditions were specified for study. The aspects of these plausible energy futures, or scenarios that are of most interest for the air qualities analysis are described in the following sections.

3.1 Coal-Dominated Scenarios

The five scenarios chosen for the most detailed impact analysis call for the continued use of coal for electrical generation in the ORBES region through the year 2000. However, a variety of policy assumptions differentiate these coal-dominated futures from each other.

As shown in figure 3-1, the base case (scenario 2) is the scenario to which all others are compared. Although the base case is relatively conventional in terms of its assumptions about the ORBES region--following historical trends--there are two major exceptions. The first exception is that the assumed rate of regional electricity demand growth is historic only through 1985. From 1985 through 2000 a lower rate is assumed. The second major exception is that full compliance with air environmental regulations is assumed; to date, however, such compliance has not been achieved.

Figure 3-1 also shows the basic variations between the base case (scenario 2) and the other coal-dominated scenarios. The second coal-dominated future, the strict environmental control case (scenario 1), differs from the base case only with regard to the stricter environmental regulations assumed. On the other hand, air quality regulations are less stringent than those of the base case in the scenario in which noncompliance with state implementation plans is assumed (scenario 2d). A high rate of growth in the demand for electricity is another variation of base case conditions (scenario 7). In the final coal-dominated future, the electrical exports case (scenario 2a), it is assumed that an additional 20,000 megawatts electric over that of the base case will be installed in the ORBES region. The electricity generated would be transmitted to the northeastern United States to replace oil-fired generation in that part of the country.

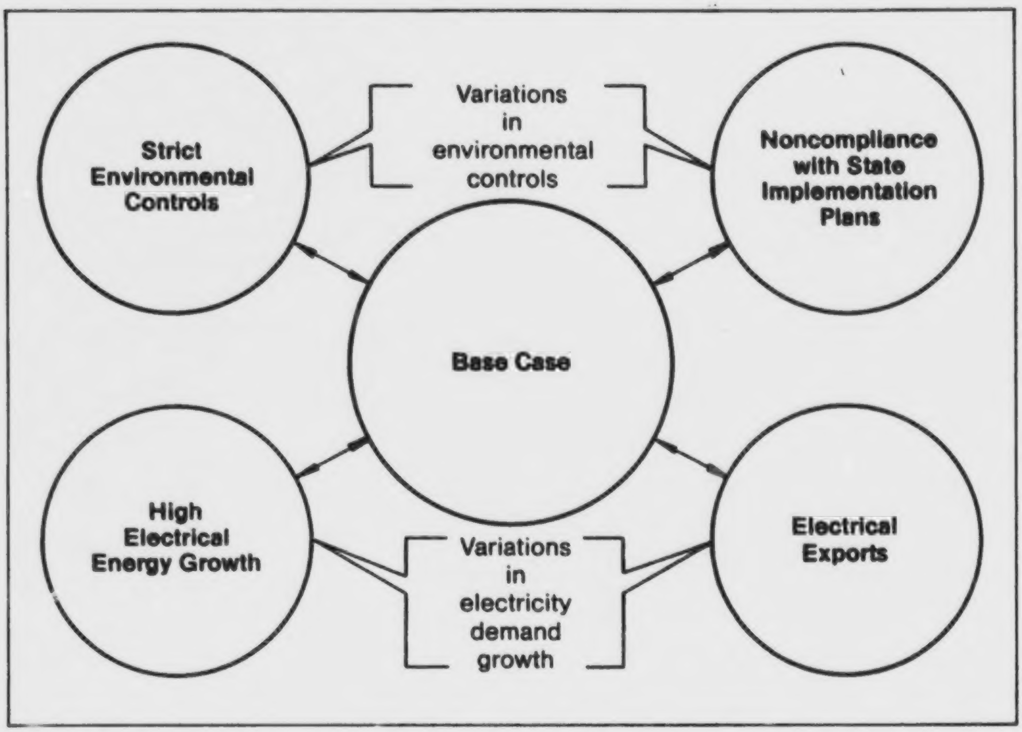
Strict Environmental Controls
Variations in environmental controls
Noncompliance with State Implementation Plans
Base Case
High Electrical Energy Growth
Variations in electricity demand growth
Electrical Exports

Figure 3-1. Major variables and comparisons, base case and other coal-dominated scenarios.

3.1.1 Environmental Standards

Among the coal-dominated scenarios, environmental standards are assumed to be the same for the base case (scenario 2), the high electrical energy growth case (scenario 7), and the electrical exports case (scenario 2a). Most of these assumed standards are defined in terms of what currently exists as applied to present and future sources of pollution. For air, controls are defined as the application of existing standards (as of September 1978) contained in the state implementation plans (SIPs) developed for specific states under the Clean Air Act. Currently SIPs for sulfur dioxide and particulates exist in all six of the ORBES states. A SIP for oxides of nitrogen exists only in the urban areas of Illinois (see table 3-1). New source performance standards (NSPS) or revised new source performance standards (termed RNSPS in this report) are applied to all new sources of pollution, according to when they are scheduled. With regard to environmental protection of air quality, then, the base case, the high electrical energy growth case, and the electrical exports case reflect the full implementation of current policies.

Table 3-1. Base Case (Scenario 2) Average SIP Emission Limitations, by ORBES State (pounds per million Btu)

State	Sulfur Dioxide		Oxides of Nitrogen		Total Emitted Particulates	
	Urban	Rural	Urban	Rural	Urban	Rural
Pennsylvania	0.60	1.80	-	-	0.100	0.100
Ohio	1.40	4.50	-	-	0.100	0.100
Indiana	1.21	5.00	-	-	0.100	0.100
Illinois	1.80	6.00	0.75	-	0.100	0.100
West Virginia	1.60	3.20	-	-	0.050	0.050
Kentucky	1.21	5.70	-	-	0.200	0.200

Table 3-2. Strict Environmental Control Case (Scenario 1) SIP Emission Limitations, by ORBES State (pounds per million Btu)

State	Sulfur Dioxide	Oxides of Nitrogen	Total Emitted Particulates
Pennsylvania	0.60	-	0.10
Ohio	1.40	-	0.10
Indiana	1.21	-	0.10
Illinois	1.80	0.75	0.10
West Virginia	1.60	-	0.05
Kentucky	1.21	-	0.20

The strict environmental control case (scenario 1) calls for more stringent environmental regulations. In the case of air, strict controls mean that the generally stringent pollutant emission standards for urban areas set by current (as of September 1978) state implementation plans would be applied throughout a state (see table 3-2).

In the SIP noncompliance case (scenario 2d), with regard to air, it is assumed that present state implementation plans will not be enforced.

3.1.2 Energy and Fuel Use

The coal-dominated futures are further defined by a variety of energy and fuel use characteristics; growth rates for the various sectors under each scenario appear in table 3-3.[1] The push to coal produces large percentage increases in the use of regional coal between 1974 and 2000, decreases in the use of natural gas, and modest increases in the use of refined petroleum products. Electricity growth ranges from an annual average rate of 3.13 in the base case (scenario 2), the strict environmental control case (scenario 1), and the SIP noncompliance case (scenario 2d); to 3.20 percent in the electrical exports case (scenario 2a); to 3.90 percent in the high electrical energy growth case (scenario 7). The high rate of electricity demand growth under the latter scenario is that suggested in recent estimates made by the National Electric Reliability Council (NERC).[2]

Table 3-3. Growth Rates and Installed Capacity, ORBES Region, Coal-Dominated Scenarios (1974-2000), Annual Averages

Scenario	**Economic Growth**	**Electricity Growth**	**Coal Growth**	**Natural Gas Growth**	**Refined Petroleum Growth**	**Energy Growth**	**Installed Capacity Year 2000 (MWe)**
Base Case	2.47%	3.13%	2.40%	−0.40%	0.37%	1.49%	153,245
Strict Environmental Controls	2.47%	3.13%	2.47%	−0.40%	0.37%	1.53%	153,245
Noncompliance with State Implementation Plans	2.47%	3.13%	2.40%	−0.40%	0.37%	1.53%	153,245
High Electrical Energy Growth	2.47%	3.90%	N/A	−0.40%	0.37%	N/A	178,372
Exports of Electricity	2.47%	3.20%	2.77%	−0.39%	0.43%	1.73%	173,395

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[1] For discussion, see Walter P. Page, Doug Gilmore, and Geoffrey Hewings, *An Energy and Fuel Demand Model for the Ohio River Basin Energy Study Region* (ORBES Phase II).

[2] See *Summary of Peak Load, Generating Capability, and Fossil Fuel Requirements, 1979* (National Electric Reliability Council, July 1979).

The varying assumptions about electricity demand growth lead to an installed regional electrical generating capacity of 153,245 megawatts electric in the year 2000 under the base case (scenario 2), the strict environmental control case (scenario 1), and the SIP noncompliance case (scenario 2d); 173,395 megawatts under the electrical exports case (scenario 2a). Coal-fired generating units are assumed to have 35-year lifetimes under all scenarios except the high electrical energy growth case, in which 45-year lifetimes are assumed.

3.1.3 Coal Supply

In all ORBES scenarios, it is assumed that the coal to supply regional generating units comes from Bureau of Mines (BOM) districts in the six ORBES states (districts 1 through 4 and 6 through 11). In the high-sulfur category (coal of 1.8 percent sulfur or more), the largest percentage increase in coal production between 1974 and 2000 would occur in BOM districts 1 and 3. The percentage of high-sulfur coal, both surface and underground, would remain the same among scenarios, although there would be differences among coal districts. As in the base year, districts 7 and 8 would provide no high-sulfur coal in the year 2000. In the low-sulfur category (coal of less than 1.8 percent sulfur), the largest percentage increase in production between 1974 and 2000 is assumed to occur in BOM districts 1 and 3; output in districts 7 and 8 is estimated to increase by a somewhat smaller percentage. Among the ORBES scenarios, the absolute coal tonnages arising from the various groups of districts would vary, but the percentage differences produced by these groups of districts would be the same across scenarios.[3]

3.1.4 Siting

In all ORBES scenarios, it is assumed that sited generating unit additions in the region announced by utility companies as of December 31, 1976, including both coal-fired and nuclear-fueled facilities, will be built as planned. The announced fuel type, unit size, and location are assumed to be identical to utility plans.[4] The dates on which these facilities will come on-line are assumed to be the same as those announced by the utilities.[5]

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[3] See Walter P. Page, *An Economic Analysis of Coal Supply in the Ohio River Basin Energy Study Reg*[illegible] (ORBES Phase II), and Donald A. Blome, *Coal Mine Siting for the Ohio Rive*[illegible]*sin Energy Study* (ORBES Phase II).

[4] For an inventory of existing and planned electrical generating units in the six ORBES states, see Steven D. Jansen, *Electrical Generating Unit Inventory, 1976-1986: Illinois, Indiana, Kentucky, Ohio, Pennsylvania, and West Virginia* (ORBES Phase II).

[5] Exceptions were made in the case of two scenarios (see chapter 13). See Gary L. Fowler et al., *The Ohio River Basin Energy Facility Siting Model: Methodology* (vol. I) (ORBES Phase II), for a full description of the siting methodology.

Between 1976 and 1985, the utilities have scheduled 68 coal-fired and 13 nuclear-fueled electrical generating units of varying size in the ORBES region. These 81 units total 43,799 megawatts electric. Most of this capacity will be built along the main stem of the Ohio River (about 25,500 megawatts) and its tributaries (about 10,500 megawatts). Among the ORBES state portions, most of the capacity additions are scheduled in Indiana, where over 11,000 megawatts electric are planned, 80 percent coal fired and 20 percent nuclear fueled. Illinois follows, with about 8500 megawatts electric, 52 percent coal fired and 48 percent nuclear fueled. All of the nearly 9000 megawatts electric scheduled for Kentucky are coal fired. The remaining capacity additions are accounted for in Pennsylvania (nearly 8000 megawatts electric, 77 percent coal fired and 23 percent nuclear fueled), Ohio (less than 5000 megawatts electric, 83 percent coal-fired and 17 percent nuclear fueled), and West Virginia (slightly over 2500 megawatts electric, all of it coal fired). Although additions scheduled from 1986 through the year 2000 are less certain, nonetheless they also are assumed to come on-line as planned by the utilities.

In order to fill the increment between electricity to be supplied by planned coal-fired and nuclear-fueled facilities and the demand for electricity projected under each scenario, standard 650 megawatt electric coal-fired generating units are sited in the region after 1985. No additional nuclear-fueled generating units are sited to meet the scenario demands beyond those already planned by the utilities. The siting patterns of the various scenarios differ according to the policy assumptions made for each scenario.[6]

Under the base case (scenario 2), 95 standard coal-fired units are sited in the study region after 1985. These 95 incremental units are concentrated in counties bordering the Ohio River main stem and its tributaries, particularly in the upper Ohio River Basin along the main stem, in the coalfields of southeastern Ohio, and in counties bordering the Monongahela and Allegheny rivers in Pennsylvania. (The SIP noncompliance (scenario 2d) pattern is the same as that of the base case.)[7]

Although the installed capacity under the base case, the SIP noncompliance case, and the strict control case is the same in the year 2000, the strict environmental control (scenario 1) assumptions lead to a more dispersed siting pattern for post-1985 electrical generating unit additions. Capacity additions along the middle and lower Ohio River main stem are concentrated on the reach from Cincinnati, Ohio, to Louisville, Kentucky, and in southwestern Indiana and southeastern Illinois in counties bordering the Wabash River. However, strict air quality standards restrict the number of suitable sites along the Ohio River main stem. Consequently, more units are located on smaller tributaries away from the main stem, in areas of lower water availability. Fifteen reservoirs are required to accommodate the dispersed siting pattern.[8]

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[6] See Gary L. Fowler et al., *The Ohio River Basin Energy Facility Siting Model: Sites and On-Line Dates* (vol. II) (ORBES Phase II).

[7] The siting patterns of all the coal-dominated scenarios appear in Fowler et al., *The Ohio River Basin Energy Facility Siting Model* (vol. II).

The installed capacity is higher under the two remaining coal-dominated scenarios, the high electrical energy growth case (scenario 7) and the electrical exports case (scenario 2a). Under the high electrical energy growth scenario, additional units over those of the base case are sited off the Ohio River main stem, on its major tributaries. Under the electrical exports case, 20,000 megawatts electric over the base case are sited to replace oil-fired capacity on the East Coast with coal-fired capacity in the ORBES region. Because of the distances involved in "transporting" the electricity to the East, the additional units are sited in the eastern portion of the ORBES region and in close proximity to major coalfields. Those units dedicated to exports are added to existing utility sites (either announced or designated in the base case). Each county with scenario unit additions is limited to a total megawattage of 2600.

Table 3-4 presents the number of scenario unit additions for each of the coal-dominated scenarios.

Table 3-4. Coal-Fired Capacity Additions, ORBES Region, Coal-Dominated Scenarios, 1986-2000

	Number of Scenario Unit Additions			
ORBES State Portion	**Base Case and SIP Noncompliance**	**Strict Environmental Controls**	**High Electrical Energy Growth**	**Exports of Electricity**
Illinois	13	13	18	13
Indiana	18	18	25	18
Kentucky	16	16	28	18
Ohio	20	20	32	33
Pennsylvania	14	14	16	19
West Virginia	14	14	25	25
Total Units	95	95	144	126

Note: Standard coal-fired capacity additions are 650 megawatts electric per unit. Included in the figures are units scheduled by the utilities through 2000; these units are of varying megawattage.

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[8] For details, see E. Downey Brill, Jr., et al., *Potential Water Quantity and Water Quality Impacts of Power Development Scenarios on Major Rivers in the Ohio Basin* (ORBES Phase II).

3.1.5 Air-Related Variations

Two variations of the high electrical growth case (scenario 7) also were examined in the air quality analyses. One variation is identical to the high growth case in all respects except that a 35-year generating unit lifetime is assumed. This case is called the high-growth, 35-year case (scenario 7b). In the second variation, generating units in the ORBES region are projected to come on-line, or to be dispatched, in the order of least sulfur dioxide emissions, rather than least cost, which is assumed in the high electrical energy growth case (and in all other scenarios). Otherwise, this latter variation, called the least emissions dispatch case, (scenario 7a), is identical to the high growth case.

3.2 Fuel Substitution and Conservation Emphasis Scenarios

The four scenarios discussed in this section reflect assumptions about energy and fuel use characteristics that differ from those of the coal-dominated futures. Three of these scenarios assume somewhat less emphasis on coal use for electrical generation because of partial substitution by other fuels. In the natural gas substitution case (scenario 4), natural gas is substituted for other fuels whenever practicable, except to fire utility boilers. In the nuclear substitution case (scenario 2c), nuclear-fueled electrical generating capacity substitutes directly for coal-fired capacity. In the alternative fuel substitution case (scenario 3), a variety of alternative fuels, including biomass and solar energy, partially replace coal-fired capacity. The fourth case (scenario 6) assumes that, because of the implementation of conservation measures, energy growth in the ORBES region is significantly less than under all other scenarios. As shown in figure 3-2, all four cases are compared directly with the coal-dominated base case; comparisons also are made among the fuel substitution and conservation scenarios themselves. Base case environmental controls also are assumed for all four scenarios.

3.2.1 Energy and Fuel Use

There is great variation, however, in the energy and fuel use characteristics that define the fuel substitution and conservation scenarios.[9] Growth rates for the various sectors appear in table 3-5, which includes base case rates as well as those for the four cases under discussion. In the natural gas substitution case (scenario 4), natural gas supplies 57 percent of the heat required for industrial processes in 1985 and 85 percent in 2000, compared with 37 percent and 10 percent, respectively, under the base case. This difference is reflected in significantly lower rates of electricity demand growth and coal growth and a significantly higher rate of natural gas growth. With nuclear substitution (scenario 2c), however, energy and fuel use characteristics are about the same as in the base case, except for a reduction in the use of coal corresponding to the replacement of coal-fired by nuclear-fueled electrical generating capacity under this

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[9] See Page, Gilmore, and Hewings, *An Energy and Fuel Demand Model.*

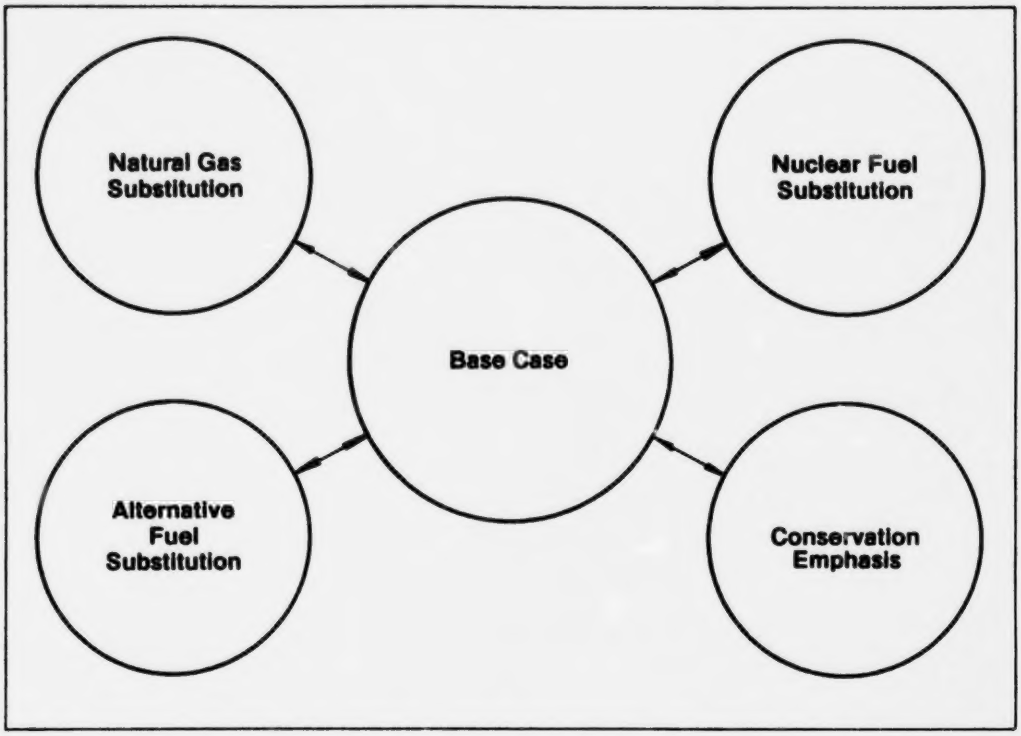
Natural Gas Substitution
Nuclear Fuel Substitution
Base Case
Alternative Fuel Substitution
Conservation Emphasis

Figure 3-2. Major variables and comparisons, base case, fuel substitution scenarios, and conservation emphasis scenario.

Table 3-5. Growth Rates and Installed Capacity, ORBES Region, Base Case, Fuel Substitution Scenarios, and Conservation Emphasis Scenario (1974-2000), Annual Averages

Scenario	Economic Growth	Electricity Growth	Coal Growth	Natural Gas Growth	Refined Petroleum Growth	Energy Growth	Installed Capacity Year 2000 (MWe)
Base Case	2.47%	3.13%	2.40%	−0.40%	0.37%	1.49%	153,245
Natural Gas Substitution	2.47%	2.00%	0.74%	3.55%	0.51%	1.61%	113,595
Nuclear Substitution	2.47%	3.11%	1.52%	−0.40%	0.37%	1.50%	145,295
Alternative Fuel Substitution	2.47%	2.69%	1.73%	−1.20%	0.15%	0.95%	134,295
Conservation	2.47%	0.90%	0.20%	−0.31%	−0.54%	0.10%	104,495

scenario. On the other hand, under the alternative fuel substitution case (scenario 3), growth in conventional energy sectors is much lower than under the base case and all other scenarios except the conservation emphasis case. This lower growth occurs because of limitations placed on end uses of the fuels emphasized in the other ORBES scenarios. Natural gas experiences an especially sharp decline under alternative fuel substitution. Among all the ORBES scenarios, the conservation emphasis case (scenario 6) results in the smallest overall energy growth rate, which is reflected in all sectors. For example, the demand for electricity under the conservation case grows at an annual average rate of 0.90 percent annually, compared with 3.13 percent under the base case.[10]

The same assumptions about the location and sulfur content of coal to supply scenario demands are made under the fuel substitution and the conservation scenarios as were made under the coal-dominated futures. Although the absolute tonnages of coal arising from different Bureau of Mines districts are lower in all these cases than under the base case (scenario 2), the percentages remain the same across scenarios.[11]

3.2.2 Siting

The same method of projecting the generating unit additions needed to meet electricity demand was used for both the coal-dominated scenarios and the fuel substitution and conservation scenarios.[12] In general, the base case (scenario 2) pattern was followed for the fuel substitution and conservation cases, with subtractions as necessary. However, under the two scenarios that call for the fewest coal-fired additions--natural gas substitution (scenario 4) and conservation emphasis (scenario 6)--the relatively few additions are located in those counties that, according to base case environmental controls, are the most suitable. As implied above, the conservation case calls for the fewest capacity additions between 1986 and 2000 among all the ORBES scenarios.

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[10] The major assumptions of the alternative fuel substitution case concerning the replacement of coal-fired capacity in the region with less conventional fuels were implemented by prorating national data reported in the Technology Assessment of Solar Energy (TASE) to the ORBES region. See Y. M. Shiffman, *TASE Project: DPR Data Base and Maximum Practical Solar Case Disaggregations* (MITRE, WP-79W-00110, 1979), and *Technology Assessment of Solar Energy: Description of Solar Technology and Energy Scenarios* (MITRE, WP-79W-0028, vols. II and III, 1979); Page, Gilmore, and Hewings, *An Energy and Fuel Demand Model;* and Walter P. Page and John Gowdy, *Gross Regional Product in the Ohio River Basin Energy Study Region, 1960-1975* (ORBES Phase II).

[11] See Blome, *Coal Mine Siting,* and Page, *An Economic Analysis of Coal Supply.*

[12] See Jansen, *Electrical Generating Unit Inventory, 1976-1986;* Gary L. Fowler et al., *The Ohio River Basin Energy Facility Siting Model,* volumes I and II.

In both the conservation emphasis scenario (scenario 6) and the natural gas substitution scenario (scenario 4), the on-line dates of selected capacity additions planned by the utilities are delayed to permit an approximately equal annual increment of additions over the study period, as in all the other scenarios. If some planned additions were not rescheduled under this overall low growth rate in regional electrical generating capacity, there would be negative growth rates in capacity between 1985 and 2000. Finally, a 35-year generating unit lifetime is assumed for the three fuel substitution scenarios and the conservation emphasis scenario.

Under the nuclear substitution case (scenario 2c), regional generating unit additions after 1985 are both nuclear fueled and coal fired. The nuclear substitution case is the only scenario in which nuclear-fueled capacity additions are sited. Distribution of the nuclear-fueled units is based on three major factors. First, the current practice of locating only coal-fired capacity in Kentucky and West Virginia is assumed to continue, and thus no nuclear-fueled units are sited in those states. Second, scenario unit additions in other state subregions are allocated with preference to counties where utilities have announced nuclear-fueled plants whose capacity can be expanded or to counties where such plants already are in operation. Third, nuclear-fueled scenario unit additions are allocated to counties independent of the location of planned or scenario-designated coal-fired generating capacity.[13]

The number of scenario unit additions for the fuel substitution cases and the conservation case appear in table 3-6. For purposes of comparison, table 3-6 also includes the number of additions for the base case.

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[13] The siting patterns for the nuclear fuel substitution scenario, the natural gas substitution scenario, the alternative fuel substitution scenario, and the conservation emphasis scenario appear in Fowler et al., *The Ohio River Basin Energy Facility Siting Model* (vol. II).

Table 3-6. Coal-Fired and Nuclear-Fueled Capacity Additions, ORBES Region: Base Case, Fuel Substitution Scenarios, and Conservation Emphasis Scenario, 1986-2000

	Number of Scenario Unit Additions					
ORBES State Portion	**Base Case**	**Natural Gas Substitution**	**Nuclear Substitution**		**Alternative Fuel Substitution**	**Conservation Emphasis**
	coal	**coal**	**coal**	**nuclear**	**coal**	**coal**
Illinois	13	4	4	19	9	2
Indiana	18	7	6	7	13	4
Kentucky	16	5	4	0	11	2
Ohio	20	8	8	2	14	6
Pennsylvania	14	4	4	5	9	2
West Virginia	14	6	6	0	10	4
Total Units	95	34	32	33	66	20

Note: Standard coal-fired capacity additions are 650 megawatts electric per unit. Standard nuclear-fueled capacity additions are 1000 megawatts electric per unit. Included in the figures are units scheduled by the utilities through 2000; these units are of varying megawattage.

Chapter 4
CURRENT CONDITIONS

This chapter presents the regional scale air quality impacts for each of the scenarios discussed in chapter 3. The regional scale SO_2 and $SO_4^=$ impacts were calculated by the Prahm regional episode transport and the TRI/Fay models using the same input parameters as for the model evaluations discussed in chapter 2. The August 25-29, 1974, period with extremely persistent winds blowing from the lower to the upper Ohio River region was selected for calculation of future episode impacts because the interpretation of the results is straightforward and because it is the most frequently occurring type of sulfate episode.

4.1 Base Case (Scenario 2)

In the base case evaluation, the major cluster of planned and scenario addition coal-fired units is projected to occur between Louisville, Kentucky, and Cincinnati, Ohio. The most important finding in the base case evaluation is that in the year 2000 utility emissions in the six ORBES states still would represent a major regional source of emissions, even though emissions from the region's coal-fired plants are projected to decrease from current levels by that year.

- Under the base case in the year 2000, utility sulfur dioxide emissions in the ORBES region still would constitute about one-third of national utility sulfur dioxide emissions. (see figure 4-1).

- Under the base case, total utility emissions would follow a pattern similar to emissions from SIP-governed units (see figure 4-2).

- The assumption that SIP units will achieve full compliance by 1985 would reduce total utility emissions as well as emissions from SIP units between 1976 and 1985.

- Between 1985 and 2000, both total utility and SIP emissions would decline because of the assumption that SIP units would be retired after 35 years. However, such retirements after 1985 also would result in an increase in emissions from RNSPS units as more such units replace the retired SIP plants.

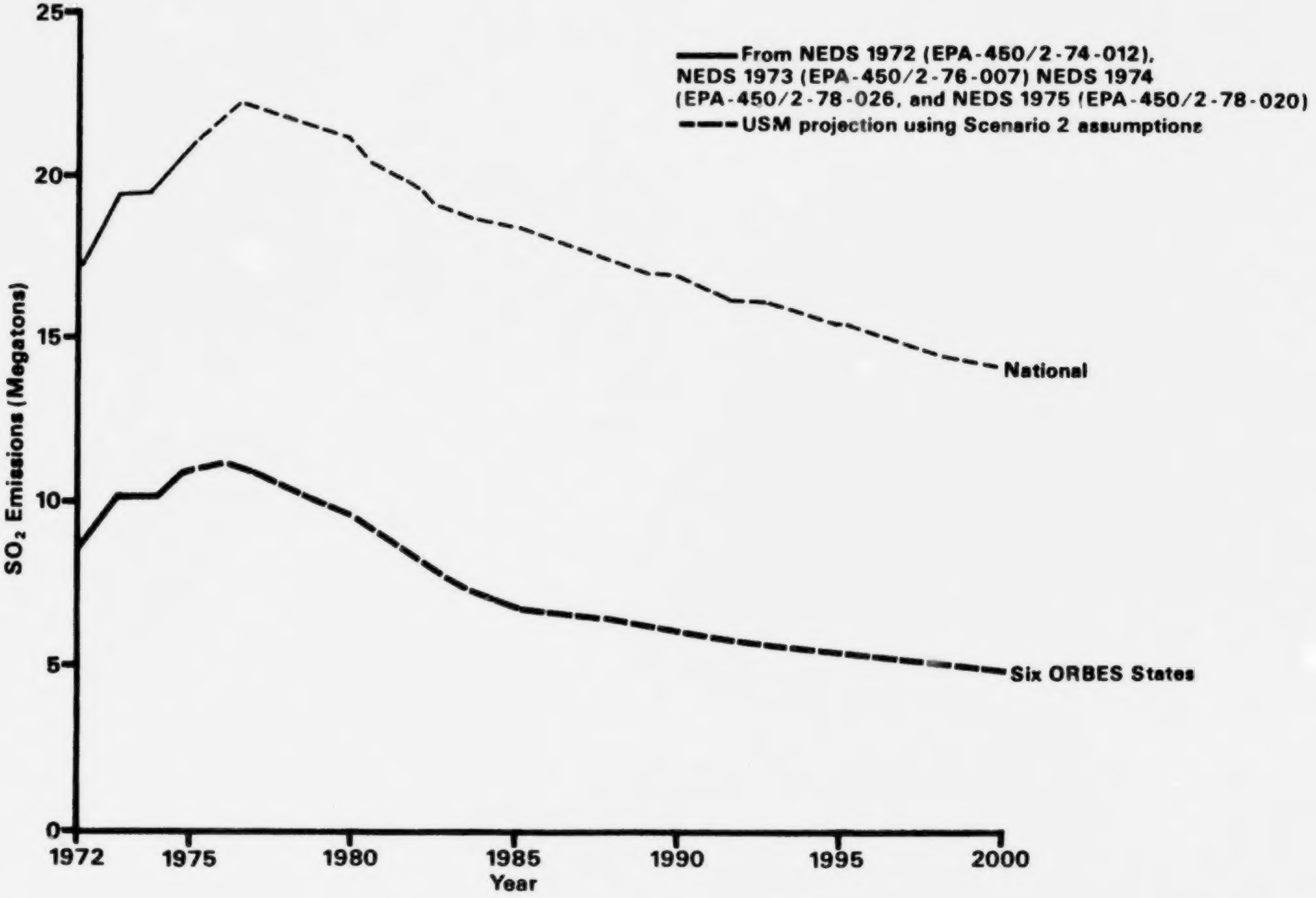

Figure 4-1. ORBES and national utility SO_2 emissions under scenario 2 (base case with SIP compliance).

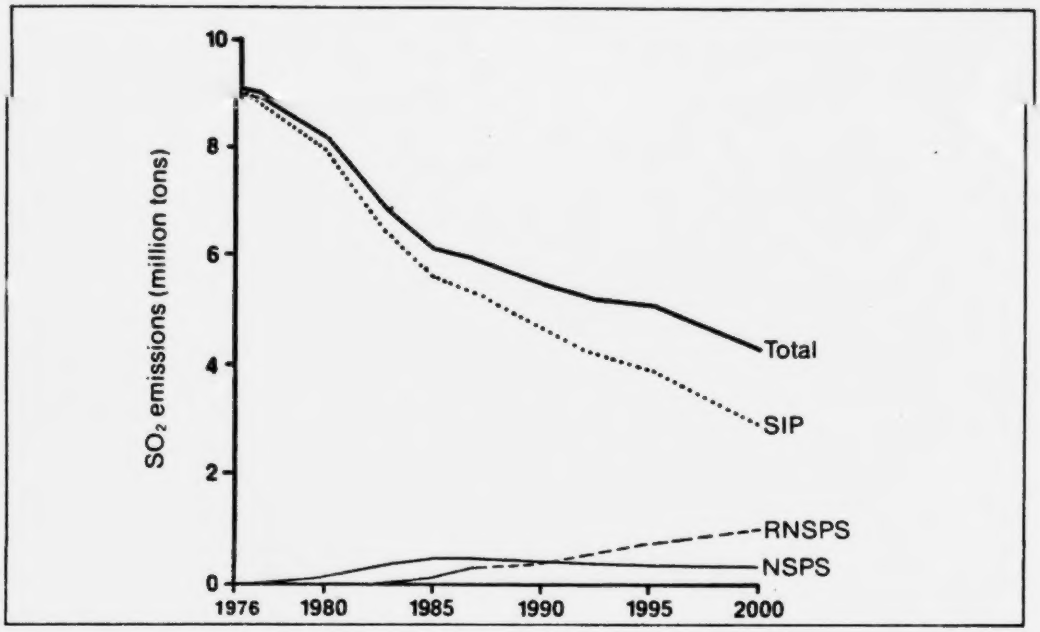

Figure 4-2. Electric utility sulfur dioxide emissions in the ORBES region, base case, by unit type.

- In terms of absolute numbers, sulfur dioxide emissions from SIP-regulated generating units in the ORBES region would decrease to 5.6 million tons in 1985 and to 2.93 million tons in 2000 from the 8.94 million tons emitted in 1976 by coal-fired electrical generating units in the region (see table 4-1).

- Sulfur dioxide emissions from all electrical generating units in the ORBES region--those regulated by SIPs, NSPS, and RNSPS--would decrease to 6.1 million tons in 1985 (a 32 percent decrease) and to 4.35 million tons in 2000 (a 51 percent decrease) from the 8.94 million tons generated in 1976 from all units in the region (see table 4-2).[1]

Despite the decrease in SIP emissions and the increase in RNSPS emissions, SIP emissions still would be the key to further reductions of the emissions projected under the base case. RNSPS units already are very clean units, removing approximately 90 percent of their potential sulfur dioxide emissions. In fact, five or six RNSPS units produce about the same amount of sulfur dioxide emissions as an average complying SIP unit that supplies the equivalent amount of electricity.

Table 4-1. SO_2 Emissions from SIPs in ORBES (Million Tons)

Year	Scenario						
	1	2	2d	4	7	7a	7b
1976	8.94	8.94	8.94	8.94	8.94	8.94	8.94
1980	6.89	7.95	9.50	7.51	7.65	6.82	7.67
1985	2.49	5.60	9.88	5.36	5.45	4.14	5.45
1990	1.94	4.73	9.00	4.76	5.20	2.97	4.64
1995	1.55	3.98	7.85	3.89	4.91	2.23	3.90
2000	1.15	2.93	6.47	3.05	4.32	1.50	2.90

Table 4-2. SO_2 Emissions (Million Tons) under Alternative Scenarios

Year	Scenario						
	1	2	2d	4	7	7a	7b
1976	8.94	8.94	8.94	8.94	8.94	8.94	8.94
1980	7.08	8.14	9.62	7.65	7.84	7.14	7.88
1985	2.99	6.10	10.10	5.66	5.93	4.69	5.94
1990	2.74	5.55	9.45	5.13	6.07	3.94	5.61
1995	2.73	5.16	8.66	4.54	6.24	3.68	5.34
2000	2.55	4.35	7.55	3.93	6.06	3.34	4.71

- As a result of the comparative "dirtiness" of SIP units, in the year 2000 they would account for approximately 67 percent (or 2.93 million tons) of all utility sulfur dioxide emissions in the ORBES region. However, these units would account for only 24 percent of the electricity generated.

- Thus, although SIP standards would reduce emissions from the 1976 levels, other strategies would be required to achieve a more balanced emission-generation ratio between 1985 and 2000.

Nonutility sulfur dioxide emissions in the ORBES region would increase by about 30 percent between 1975 and 2000, based on some recent, highly approximate projections. As a result of such increases, nonutility emissions would make up a larger fraction of the total sulfur dioxide emissions in 2000 than they did in 1975. Thus, while nonutility emissions accounted for approximately 20 percent of all sulfur dioxide emissions in 1975, these emissions would account for approximately 29 percent of all sulfur dioxide emissions in 2000 under the base case.

- As a result of the increased nonutility emissions and the decreased utility emissions, total sulfur dioxide emissions in the ORBES region would decrease by about 40 percent by the year 2000 from the total emissions of this pollutant in 1975 (see figure 4-3).

Total regional particulate emissions would continue to be dominated by nonutility emissions under the base case, as they were during the base period.

- Under the base case, particulate emissions in 1985 and 2000 from all electrical generating units in the ORBES region would decrease to 250,000 tons (an 82 percent decrease) and 190,000 tons (an 86 percent decrease), respectively, from the 1.38 million tons generated in 1976 by all units in the region (see table 4-3).

Nonutility particulate emissions in the ORBES region also would decrease (by about 60 percent) under the base case between 1976 and 1985, again according to some recent, highly approximate projections. However, between 1985 and 2000, regional nonutility particulate emissions would in-

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[1] A higher power plant capacity factor and a lower BTU content for coal were assumed in the utility simulation model analysis than was assumed by other ORBES researchers. The combined effect of these differences in assumptions is a higher coal use estimate in the ORBES region in the year 2000. For a discussion of these different assumptions, see Teknekron Research, Inc., *Selected Impacts of Electric Utility Operations in the Ohio River Basin (1976-2000): An Application of the Utility Simulation Model, Vol. III.*

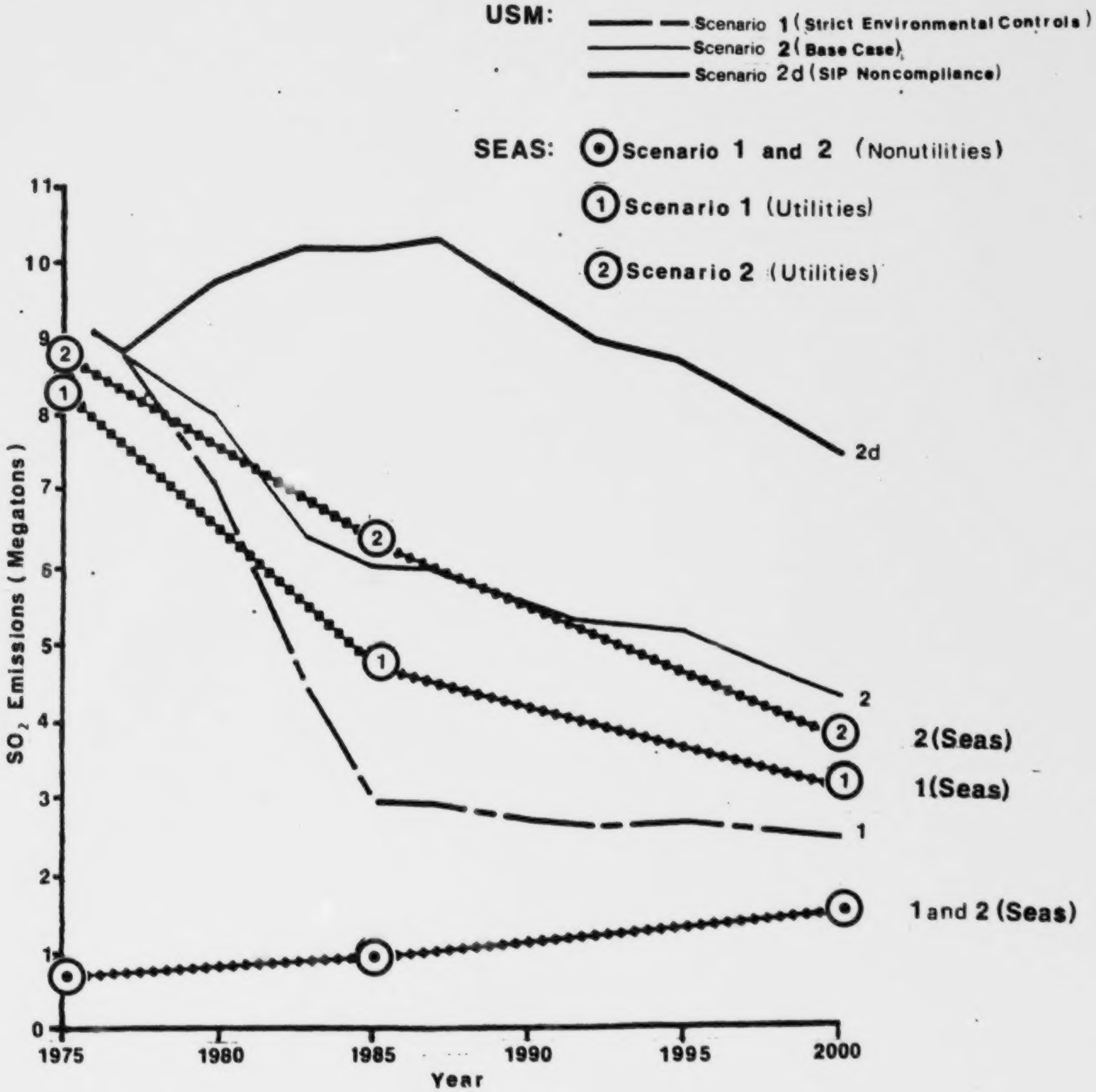


Figure 4-3. Annual SO_2 emissions in the ORBES region under alternative SIP scenarios.

Table 4-3. Electric Utility Particulate Emissions (10^6 Tons) under Alternative Scenarios

	Scenario						
Year	1	2	2d	4	7	7a	7b
1976	1.38	1.38	1.38	1.38	1.38	1.38	1.38
1980	0.83	0.83	1.44	0.83	0.83	0.79	0.83
1985	0.25	0.25	1.53	0.22	0.25	0.24	0.25
1990	0.24	0.22	1.37	0.20	0.25	0.23	0.23
1995	0.23	0.21	1.23	0.18	0.26	0.23	0.23
2000	0.21	0.19	1.06	0.16	0.26	0.21	0.21

crease by about 30 percent from their 1985 levels. (The different growth rates assumed for the utility and nonutility sectors result in the decrease in utility emissions and the increase in nonutility emissions after 1985.)

- Since nonutility emissions decrease between 1976 and 2000 and account for about 75 percent of the total regional particulate emissions, total particulate emissions would decrease about 60 percent by 1985 from the 1976 levels and would increase about 14 percent during the period between 1985 and 2000 (see figure 4-4).

Annual utility emissions of oxides of nitrogen, on the other hand, would increase between 1976 and 2000 because no SIP standards for oxides of nitrogen exist in the ORBES region, except in the urban areas of Illinois. Thus, the greater the electricity demand growth, the greater the emissions.

- By 1985 under the base case, utility nitrogen oxide emissions would total 1.71 million tons (a 15 percent increase over the 1976 levels of 1.49 million tons). By 2000, they would total 2 million tons (a 34 percent increase from the 1976 levels). See table 4-4.

As a result of decreased utility sulfur dioxide emissions under the base case, regional utility emissions should contribute less to regional sulfur dioxide and sulfate concentrations by the year 2000 than they contributed during the base period. However, the ratio of the lower ORBES region's contribution to sulfur dioxide and sulfate concentrations in the upper region is not likely to change under the base case, or under any scenario, from the 1976 ratio.

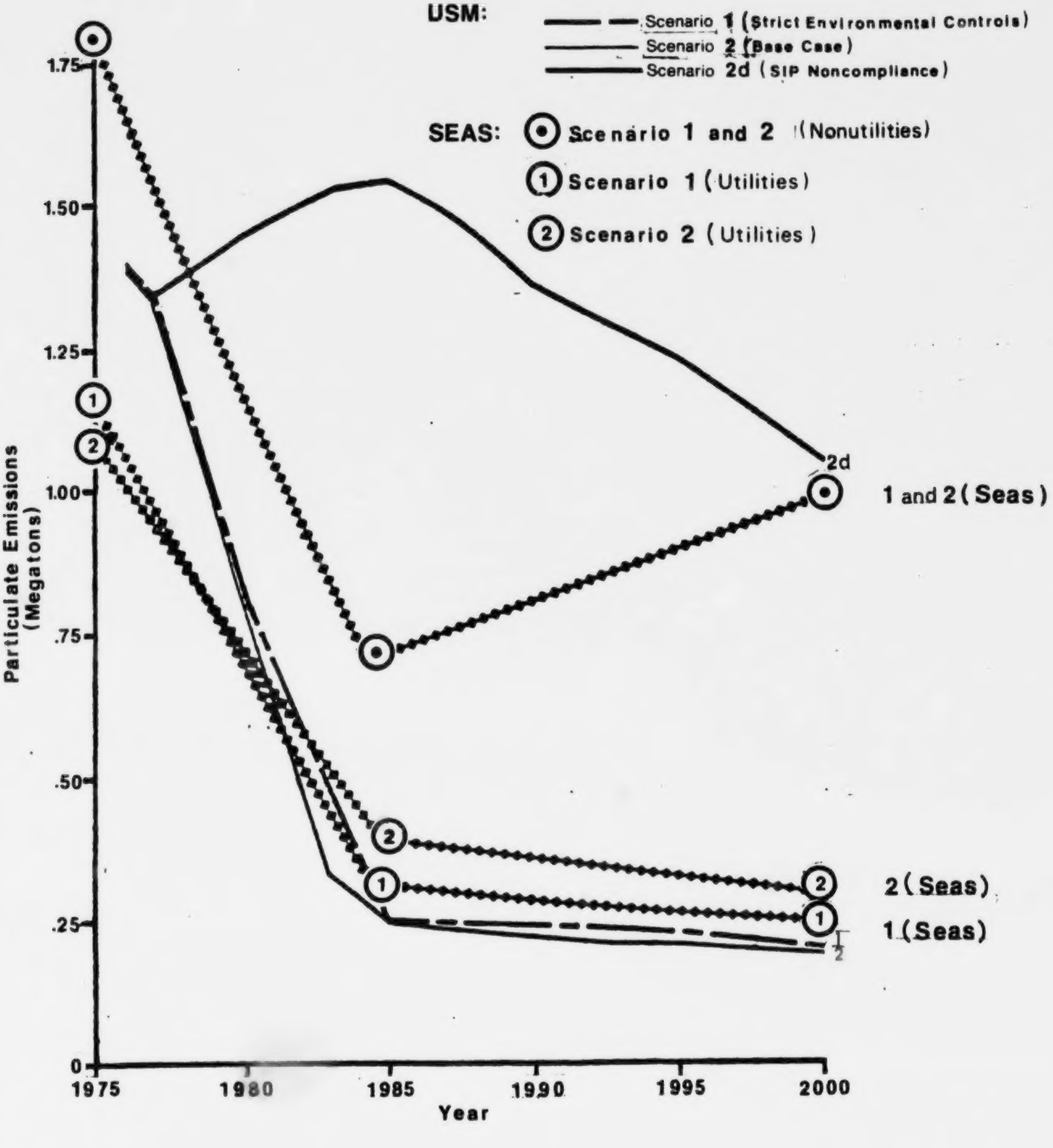


Figure 4-4. Annual particulate emissions in the ORBES region under alternative SIP scenarios.

Table 4-4. Electric Utility NO_x Emissions (10^6 Tons) under Alternative Scenarios

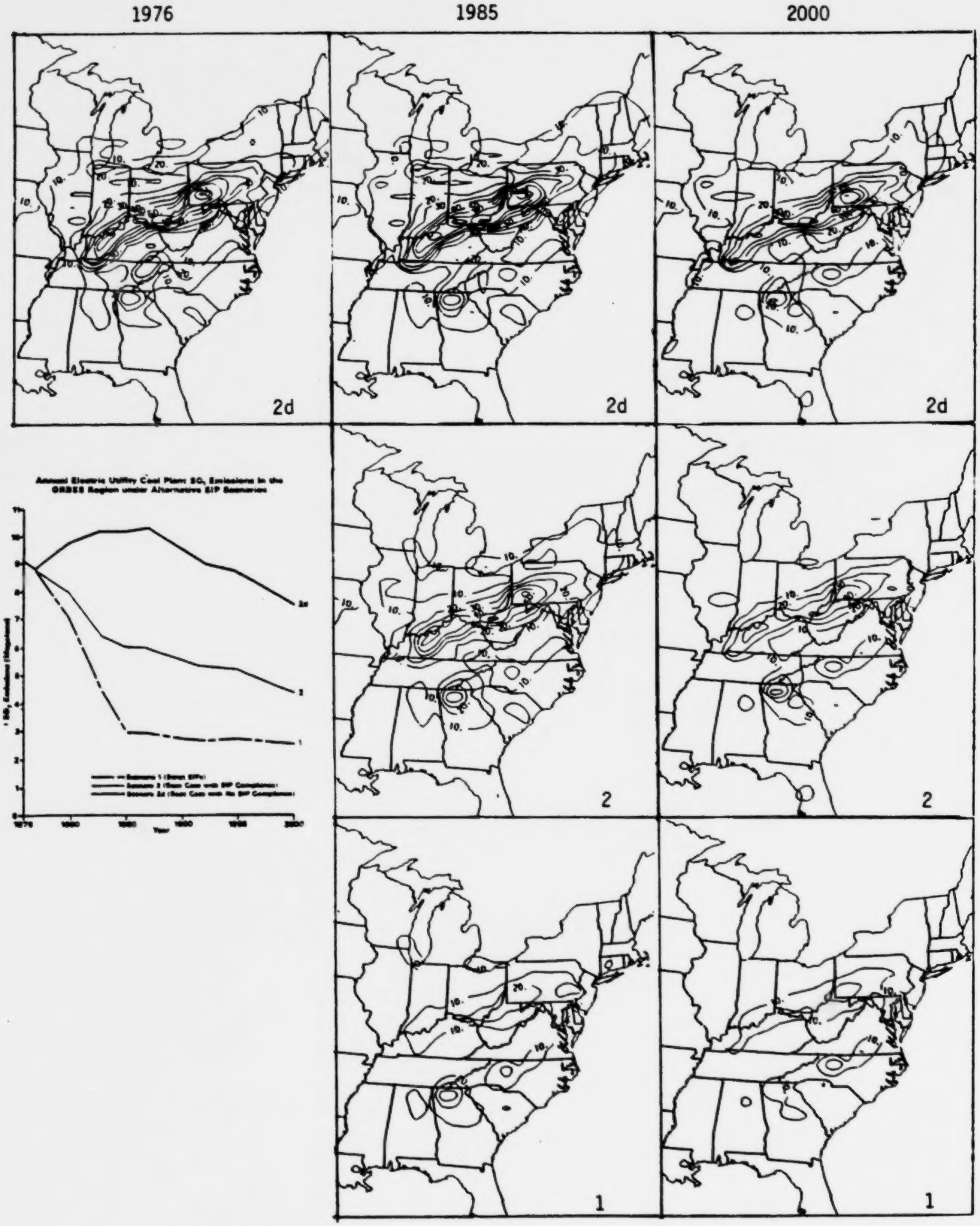
Year	Scenario 1	2	2d	4	7	7a	7b
1976	1.49	1.49	1.49	1.49	1.48	1.48	1.48
1980	1.60	1.63	1.66	1.50	1.63	1.55	1.63
1985	1.69	1.71	1.82	1.44	1.67	1.58	1.67
1990	1.74	1.77	1.88	1.38	1.93	1.79	1.86
1995	1.96	1.98	2.08	1.46	2.34	2.16	2.21
2000	1.99	2.00	2.16	1.51	2.63	2.41	2.46

If the same conditions of extremely persistent winds were to occur under the base case as those that occurred during the August 27, 1974, sulfate episode, the utility-related sulfur dioxide and sulfate concentrations would be significantly lower than they were during that episode (see figures 4-5 and 4-6).

- Sulfur dioxide and sulfate concentrations in the upper ORBES region from utility sources in all subregions should be about 50 percent lower in 2000 under the base case than concentrations that occurred on August 27, 1974, from the same sources.

- Under the base case, utility emissions from the lower ORBES region in 2000 would contribute only about 40 percent of the sulfate concentrations that they contributed to the upper region under the August 27 episode.

- Utility-related sulfur dioxide concentrations in that area that experienced the highest concentrations in 1976 would total 65.2 micrograms per cubic meter (31 percent lower) in 1985 and 48.2 micrograms per cubic meter (49 percent lower) in 2000. Sulfate concentrations in this high concentration area due to all regional utility emissions would total 30 micrograms per cubic meter (25 percent lower) in 1985 and 19.7 micrograms per cubic meter (51 percent lower) in 2000. About 12 micrograms per cubic meter of these sulfate concentrations in the year 2000 would come from utility emissions in just the lower ORBES region.



1976
1985
2000
2d
2d
2d
2
2
1
1
Annual Electric Utility Coal Plant SO2 Emissions in the ORBES Region under Alternative SIP Scenarios
SO2 Emissions (Megatons)
Year
1975
1980
1985
1990
1995
2000
0
1
2
3
4
5
6
7
8
9
10
11
Scenario 1 (Strict SIPs)
Scenario 2 (Base Case with SIP Compliance)
Scenario 2d (Base Case with No SIP Compliance)
10.
20.

Figure 4-5. Predicted sulfur dioxide concentrations under the base case (scenario 2), the strict environmental control case (scenario 1), and the SIP noncompliance case (scenario 2d) under the meteorology of August 27, 1974 .

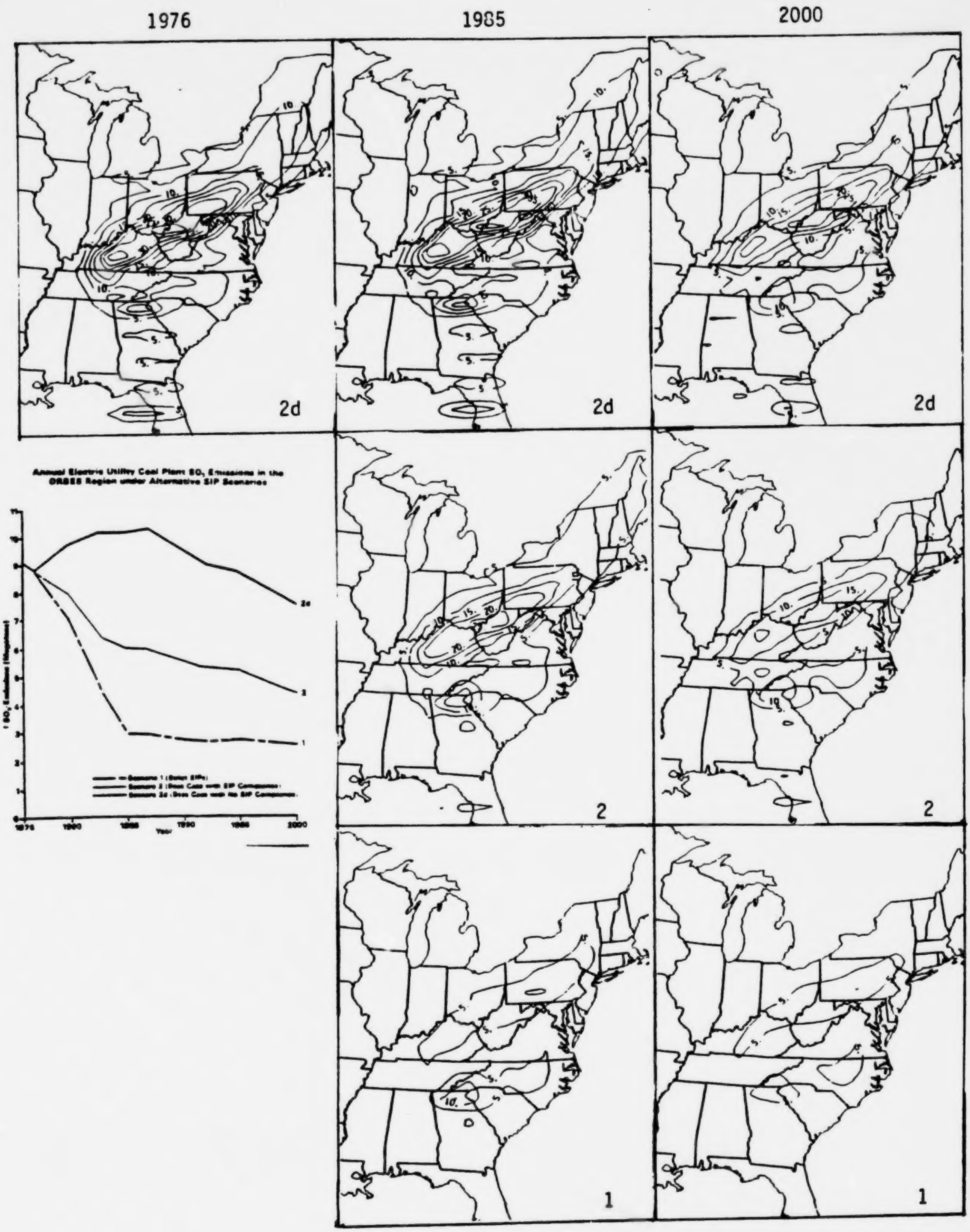

1976
1985
2000
2d
2d
2d
2
2
1
1
Annual Electric Utility Coal Plant SO2 Emissions in the ORBES Region under Alternative SIP Scenarios
SO2 Emissions (Megatons)
Year
1975
1980
1985
1990
1995
2000
0
1
2
3
4
5
6
7
8
9
10
11
2d
2
1
Scenario 1 (Strict SIPs)
Scenario 2 (Base Case with SIP Compliance)
Scenario 2d (Base Case with No SIP Compliance)

Figure 4-6. Predicted sulfate concentrations under the base case (scenario 2), the strict environmental control case (scenario 1), and the SIP noncompliance case (scenario 2d) using the meteorology of August 27, 1974.

Annual utility-related sulfur dioxide and sulfate concentrations in the ORBES region also would decrease under the base case from the 1976 regional utility-related concentrations, especially in the area with the highest annual concentrations in 1976.

- In 1985 under the base case, the annual sulfur dioxide concentration in this high concentration area would be 18.55 micrograms per cubic meter (or 28 percent lower), and the annual sulfate concentration would be 6.7 micrograms per cubic meter (or 27 percent lower).
- By 2000 under the base case, the annual sulfur dioxide concentration in this high concentration area should have decreased about 50 percent from the 1976 levels--to 12.94 micrograms per cubic meter--and the annual sulfate concentration, about 49 percent--to 4.7 micrograms per cubic meter.

Figures 4-7 and 4-8 depict the significant improvements throughout the region in annual utility-related concentrations under the base case. Figure 4-7 compares the 1976 sulfur dioxide concentrations with the projected 1985 and 2000 sulfur dioxide concentrations. As can be seen, the area affected by the highest sulfur dioxide concentrations would be significantly smaller under the base case, although the general location of the highest sulfur dioxide concentrations would remain about the same. Figure 4-8 compares the annual average sulfate concentrations in 1976, 1985, 2000 and shows the extensive improvements projected in such utility-related concentrations both within and outside of the region.

Since nonutility sulfur dioxide emissions would increase between 1976 and 2000, the annual average concentrations attributable to such emissions also would increase. However, since nonutility sulfur dioxide emissions would comprise only about 29 percent of total regional sulfur dioxide emissions in 2000, nonutility-related concentrations would be much lower than the utility-related concentrations. The annual average sulfur dioxide concentrations resulting from nonutility emissions would increase from about 2 micrograms per cubic meter in 1975 to about 4 micrograms per cubic meter in 2000. Between these same years, annual average sulfate concentrations would increase from approximately 1 microgram per cubic meter to approximately 2 micrograms per cubic meter. See figure 4-9.

4.2 Strict Environmental Control Case (scenario 1)

Under the strict environmental control case (scenario 1), there would be a greater decrease in utility sulfur dioxide emissions and in related episodic and annual concentrations than there would be under the base case (scenario 2). Utility particulate and nitrogen oxide emissions, however, would be about the same under both scenarios.

Total utility sulfur dioxide emissions in the ORBES region would be about twice as low under the strict environmental control case in both 1985

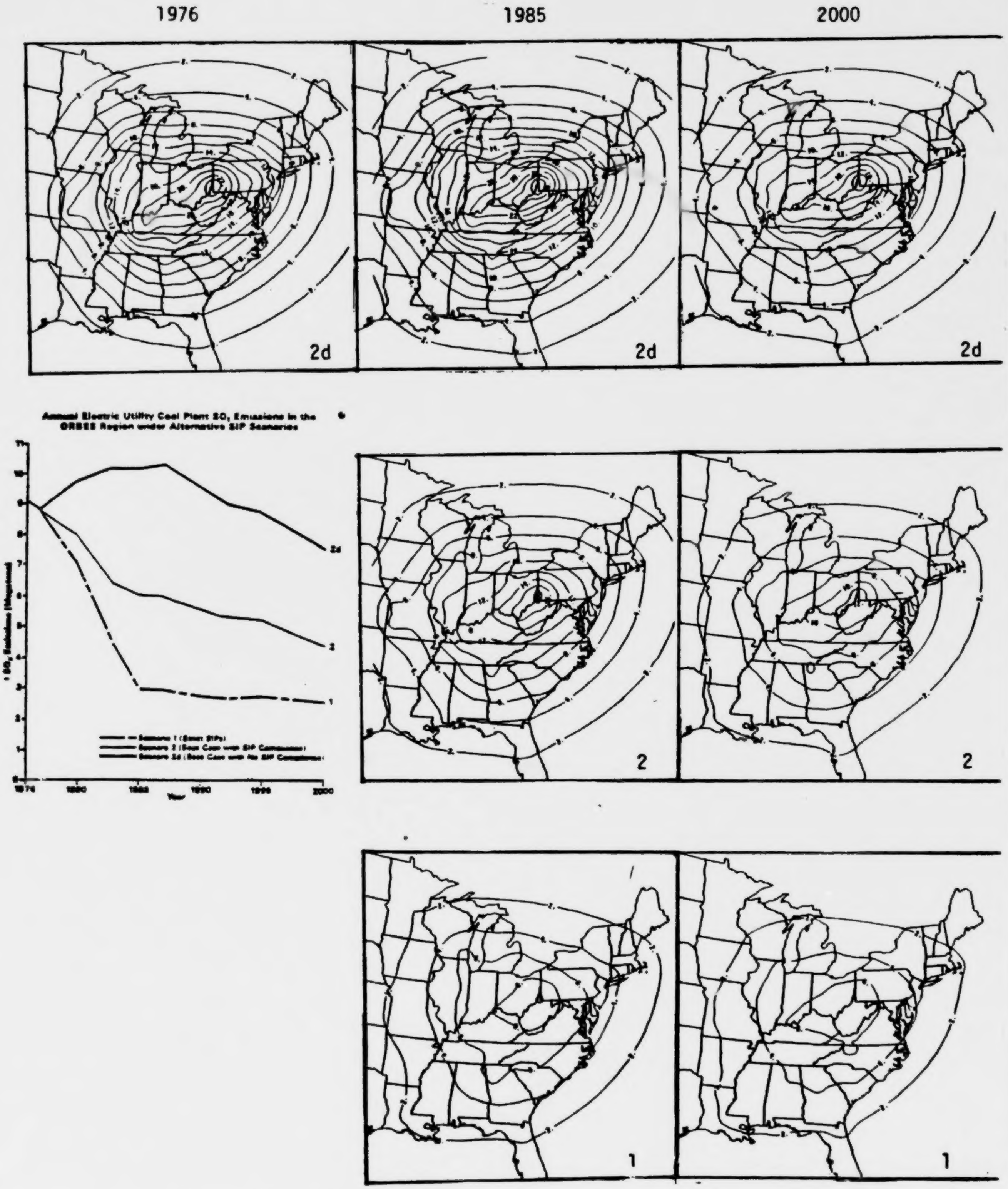

1976
1985
2000
2d
2d
2d
2
2
1
1
Annual Electric Utility Coal Plant SO_2 Emissions in the ORBES Region under Alternative SIP Scenarios
SO_2 Emissions (Megatons)
0
1
2
3
4
5
6
7
8
9
10
11
1976
1980
1985
1990
1995
2000
Year
2d
2
1
Scenario 1 (Strict SIPs)
Scenario 2 (Base Case with SIP Compliance)
Scenario 2d (Base Case with No SIP Compliance)

Figure 4-7. Predicted annual average sulfur dioxide concentrations under the base case (scenario 2), the strict environmental control case (scenario 1), and the SIP noncompliance case (scenario 2d) in 1985 and 2000.

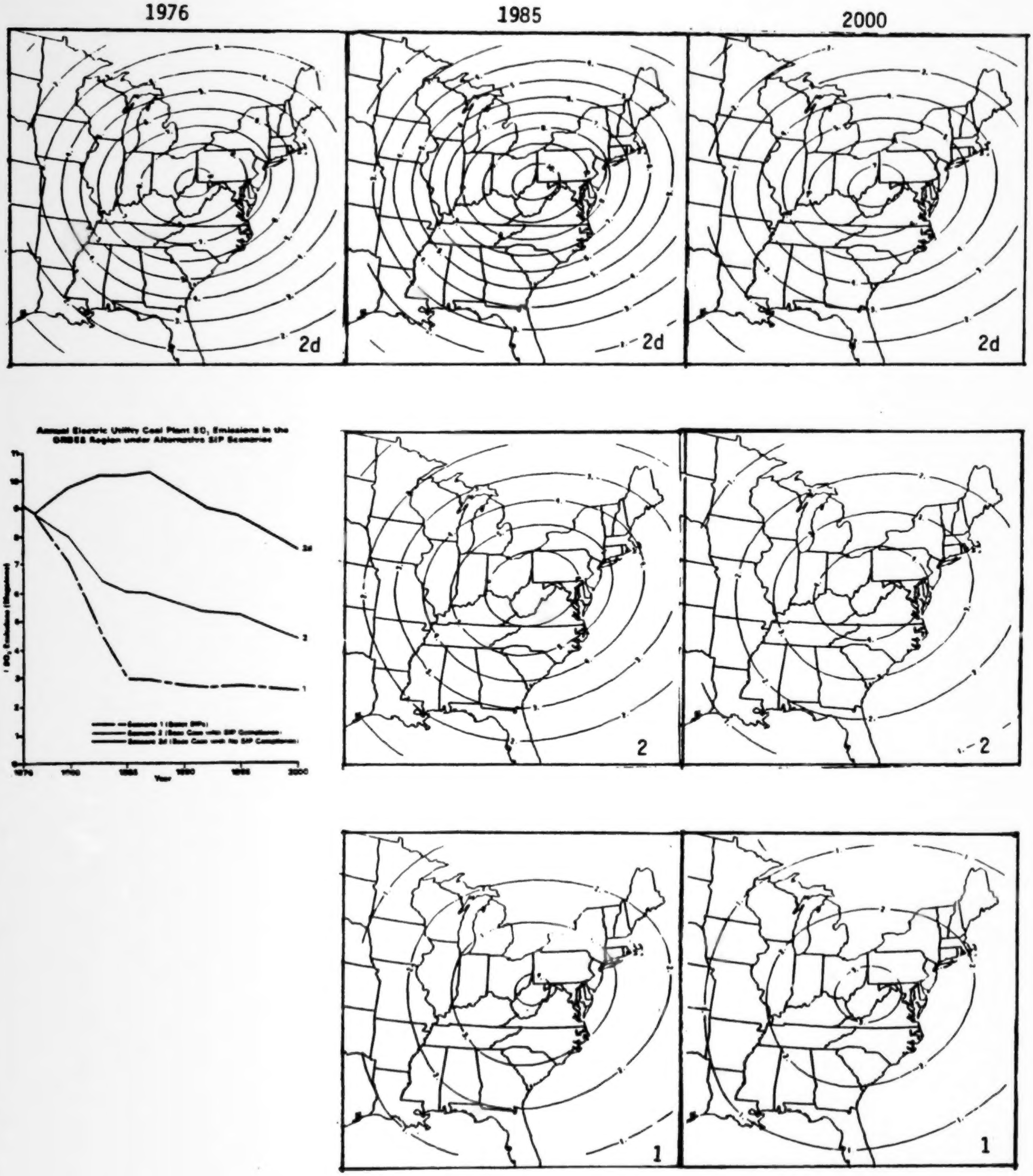
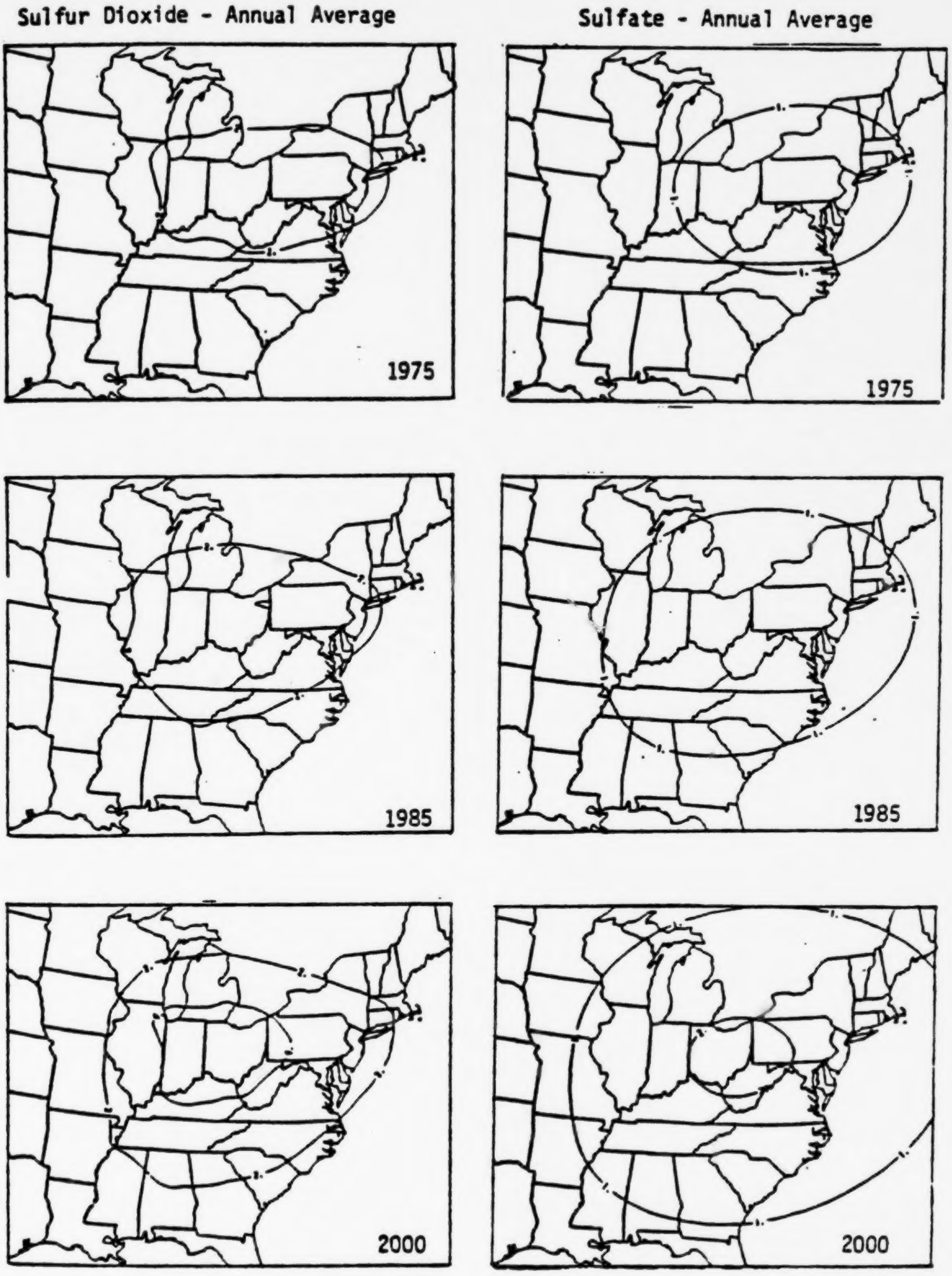

1976
1985
2000
2d
2d
2d
2
2
1
1
Annual Electric Utility Coal Plant SO_2 Emissions in the ORBES Region under Alternative SIP Scenarios
SO_2 Emissions (Megatons)
Year
1976
1980
1985
1990
1995
2000
2d
2
1
Scenario 1 (Strict SIPs)
Scenario 2 (Base Case with SIP Compliance)
Scenario 2d (Base Case with No SIP Compliance)

Figure 4-8. Predicted annual average sulfate concentrations under the base case (scenario 2), the strict environmental control case (scenario 1), and the SIP noncompliance case (scenario 2d).


Sulfur Dioxide - Annual Average

Sulfate - Annual Average

1975
1975
1985
1985
2000
2000
1.

Figure 4-9. Predicted annual average sulfur dioxide and sulfate concentrations ($\mu g/m^3$) resulting from nonutility emissions.

and 2000 as they would be under the base case in the same years (see table 4-2). This reduction would occur because urban state implementation plans (SIPs), which under strict controls would be applied throughout a state, are much stricter than rural SIPs, which would be in force in rural areas under the base case.

- Specifically, with strict environmental controls, sulfur dioxide emissions from all generating units in the ORBES region (SIP units, new source performance standards (NSPS) units, and revised new source performance standards (RNSPS) units) would be about 51 percent lower by 1985 and about 61 percent lower by 2000 than under the base case.

- Sulfur dioxide emissions from SIP units alone (see table 4-1) also would be lower (56 percent lower by 1985 and 61 percent lower by 2000).

However, emissions from these units still would make up the majority (83 percent) of all utility emissions in 1985 and a sizeable portion (45 percent) of all utility emissions in 2000. Moreover, in 2000 under the strict control case, as under the base case, SIP units would account for only 24 percent of the regional electrical generation. However, since emissions from SIP units would constitute 67 percent of all utility emissions in 2000 under the base case, the strict control case would lead to a more balanced emission-generation ratio.

- Utility particulate emissions in the ORBES region would be identical in 1985 and nearly the same in 2000 under the strict environmental control case and the base case since SIP particulate standards are assumed to be the same under both cases in both rural and urban areas. See table 4-3.

- Utility emissions of oxides of nitrogen in the ORBES region would be almost identical in 1985 and 2000 (less than 1 percent difference) under both the strict environmental control case and the base case. The primary reason for this similarity is that both of these scenarios have the same generating capacity and assume the same nitrogen oxide controls. See table 4-4.

If the same conditions of extremely persistent winds were to occur under the strict environmental control case as those that occurred during the August 27, 1974, sulfate episode, sulfur dioxide and sulfate concentrations would decrease. See figures 4-5 and 4-6.

- Under the strict environmental control case, the sulfur dioxide and sulfate concentrations related to utility emissions would be so much lower than the concentrations that occurred on August 27, 1974, that they no longer would be considered episodic.

- In the area that experienced the highest episodic concentrations under the base case in 1985, the sulfur dioxide and sulfate concentrations would be 54 and 68 percent lower, respectively, in the same year under the strict control case. In the year 2000, episodic sulfur dioxide and sulfate concentrations would be 50 and 55 percent lower, respectively, under strict controls than under the base case.

Annual regional sulfur dioxide and sulfate concentrations due to utility sulfur dioxide emissions would be substantially lower under the strict environmental control case than they would be under base case in both 1985 and 2000 (see figures 4-7 and 4-8).

- In the area that experienced the highest annual concentrations under the base case, sulfur dioxide and sulfate annual concentrations would be significantly reduced both in 1985 (by 46 and 39 percent, respectively) and in 2000 (by 42 and 33 percent, respectively).

4.3 SIP Noncompliance (scenario 2d)

If state implementation plans are not complied with (scenario 2d), regional utility sulfur dioxide and particulate emissions would be substantially higher than those under the base case (scenario 2). As under all of the coal-dominated scenarios, utility emissions of oxides of nitrogen would increase between 1976 and 2000 under the SIP noncompliance case. Regional episodic and annual sulfur dioxide and sulfate concentrations related to utility sulfur dioxide emissions also would increase under SIP noncompliance.

- Sulfur dioxide emissions from SIP-noncompliance, coal-fired generating units in the ORBES region would increase 81 percent by 1985 and 121 percent by 2000 over base case emissions levels for SIP units in those years (see table 4-1).

- Sulfur dioxide emissions from all generating units--SIP, NSPS, and RNSPS units--in the ORBES region would increase 66 percent by 1985 and 74 percent by 2000 over base case emission levels for all units in those years (see table 4-2).

Since SIP emissions would constitute 98 percent of all utility emissions in 1985 and 86 percent in 2000 under the SIP noncompliance scenario, noncompliance would be responsible for almost all of the emission-related impacts projected to occur. However, SIP units would account for only 40 percent of total regional electrical generation in 2000 under the SIP noncompliance case.

It is interesting to note the significant emission increases that are projected to occur under the SIP noncompliance case when longer generating unit lifetimes are assumed. In the year 2000, total utility sulfur dioxide emissions would be 7.55 million tons assuming a 35-year generating unit life, 10.1 million tons assuming a 45-year life, and 11.1 million tons assuming a 55-year life. Thus, utility sulfur dioxide emissions would be 25 percent higher in the year 2000 with a 45-year plant life than with a 35-year life, and 32 percent higher in that year with a 55-year life than with a 35-year life.

- In both 1985 and 2000, utility particulate emissions in the ORBES region would be as much as six times higher under the SIP noncompliance case than the emissions that would be expected under compliance, or the base case, in those years. See table 4-3.

- Utility emissions of oxides of nitrogen in the ORBES region, however, would not be significantly different in either 1985 or 2000 under the SIP noncompliance case and the base case (see table 4-4).

Similar nitrogen oxide emission levels would result because none of the ORBES states has SIP standards for nitrogen oxides, except for the urban areas of Illinois. Thus, since both scenarios have the same nitrogen oxide standards and generate about the same amount of electricity, they would result in about the same utility nitrogen oxide emissions.

If the same conditions of extremely persistent winds were to occur under the SIP noncompliance case as those that occurred during the August 27, 1974, sulfate episode, sulfur dioxide and sulfate concentrations due to utility emissions would be much higher (see figures 4-5 and 4-6).

- In 1985, in the area that experienced the highest episodic concentrations due to utilities under the base case, sulfur dioxide concentrations would be 71 percent higher; sulfate concentrations would be 42 percent higher in that area.

- By 2000, regional episodic sulfur dioxide and sulfate concentrations in the same area would be 71 and 41.6 percent higher, respectively, than under the base case in that year.

Annual concentrations in the ORBES region due to utility sulfur dioxide emissions would be substantially higher under the SIP noncompliance case than under the base case.

- In 1985, in the area that experienced the highest annual concentrations under the base case, annual sulfur dioxide and sulfate concentrations would be about 61 and 54 percent higher, respectively, than the concentrations projected under the base case for that year.

- In 2000 under SIP noncompliance, annual sulfur dioxide and sulfate concentrations in the same area would be about 64 and 56 percent higher, respectively, than the concentrations projected under the base case for that year. Figures 4-7 and 4-8 emphasize the differences between these two scenarios in annual average concentrations within the region in the year 2000.

4.4 High Electrical Energy Growth (scenario 7) and Variations (scenarios 7a and 7b)

In section 4.4.1, the effects of high electrical energy growth in the ORBES region (at an annual average rate of 3.9 percent between 1974 and 2000) are compared with those of energy growth under the base case (3.13 percent annually). The high electrical energy growth case also assumes a 45-year lifetime for new generating units, while the base case assumes a 35-year lifetime for new units. As a result of the high electrical energy growth projected, installed generating capacity in the ORBES region would be 178,372 megawatts electric in the year 2000, compared with 153,245 megawatts electric under the base case. Other than the electrical energy growth and generating unit lifetime assumptions, the base case and the high electrical energy growth case are the same.

Two variations of the high electrical growth case also were examined in the air quality analyses. One variation is identical to the high growth case in all respects except that a 35-year generating unit lifetime is assumed. This case, called the high-growth, 35-year case, is compared to the base case and to the high electrical energy growth case. In the second variation, generating units in the ORBES region are projected to come on-line, or to be dispatched, in the order of least sulfur dioxide emissions, rather than least cost, which is assumed in the high electrical energy growth case (and in all other scenarios). Otherwise, this latter variation, called the least emissions dispatch case, is identical to the high growth case and is compared to that case. These variations are discussed in section 4.4.2.

4.4.1 Scenario 7

The high electrical energy growth case (scenario 7) and the base case (scenario 2) would result in about the same utility sulfur dioxide, particulate, and nitrogen oxide emissions and about the same regional sulfur dioxide and sulfate concentrations in 1985. These emissions and concentrations would be similar in 1985 because the same generating capacity is assumed for both scenarios in that year. However, since capacity expands more under the high growth case after 1985, and since generating units have a 45-year rather than a 35-year lifetime, all emissions and concentrations would be higher under the high growth case than under the base case by the year 2000.

- Under high electrical energy growth, sulfur dioxide emissions from units regulated by state implementation plans (SIPs) would be 47 percent greater in 2000 than the emissions from SIP-regulated units under the base case in that year (see table 4-1).

- SIP emissions also would make up 71 percent of the regional utility emissions in 2000 under the high growth case, although units regulated by SIPs would account for only 25 percent of the total regional electrical generation in 2000. Additional data suggest that the majority of the increase in emissions would be attributable to the differences in plant lifetimes and not to the differences in electrical energy growth.

- Utility sulfur dioxide emissions from all units would be 39 percent higher in 2000 under high electrical growth than under the base case (see table 4-2).

- By 2000 under the high electrical energy growth case, utility particulate emissions would be 36.8 percent higher than base case levels in that year (see table 4-3).

- Similarly, utility nitrogen oxide emissions would be 31.5 percent higher in 2000 than they would be under the base case in that year (see table 4-4).

If the same conditions of extremely persistent winds were to occur under the high growth case in 2000 as those that occurred during the August 27, 1974, sulfate episode, utility-related sulfur dioxide and sulfate concentrations would be higher than under base case conditions in 2000 (see figures 4-10 and 4-11).

- In the area of highest concentrations under the base case, for example, utility-related sulfur dioxide and sulfate concentrations would be about 37 and 65 percent higher, respectively, under the high growth case.

- In the year 2000, annual regional sulfur dioxide and sulfate concentrations due to utility sulfur dioxide emissions would be about 43 and 47 percent higher, respectively, under the high electrical energy growth case in the area of highest concentration than the projected concentrations in the same area under the base case.

Figures 4-12 and 4-13 illustrate the differences between the annual concentrations under the base case and under the high growth case. Figure 4-12 compares annual sulfur dioxide concentrations in the years 1985 and 2000 under both scenarios. As this figure indicates, the area along the Ohio River main stem still would be the most affected portion of the ORBES region under high growth, although more of that area would be affected by higher concentrations. Figure 4-13 compares annual sulfate concentrations under the two scenarios. As shown by the figure, the acreage affected by the highest

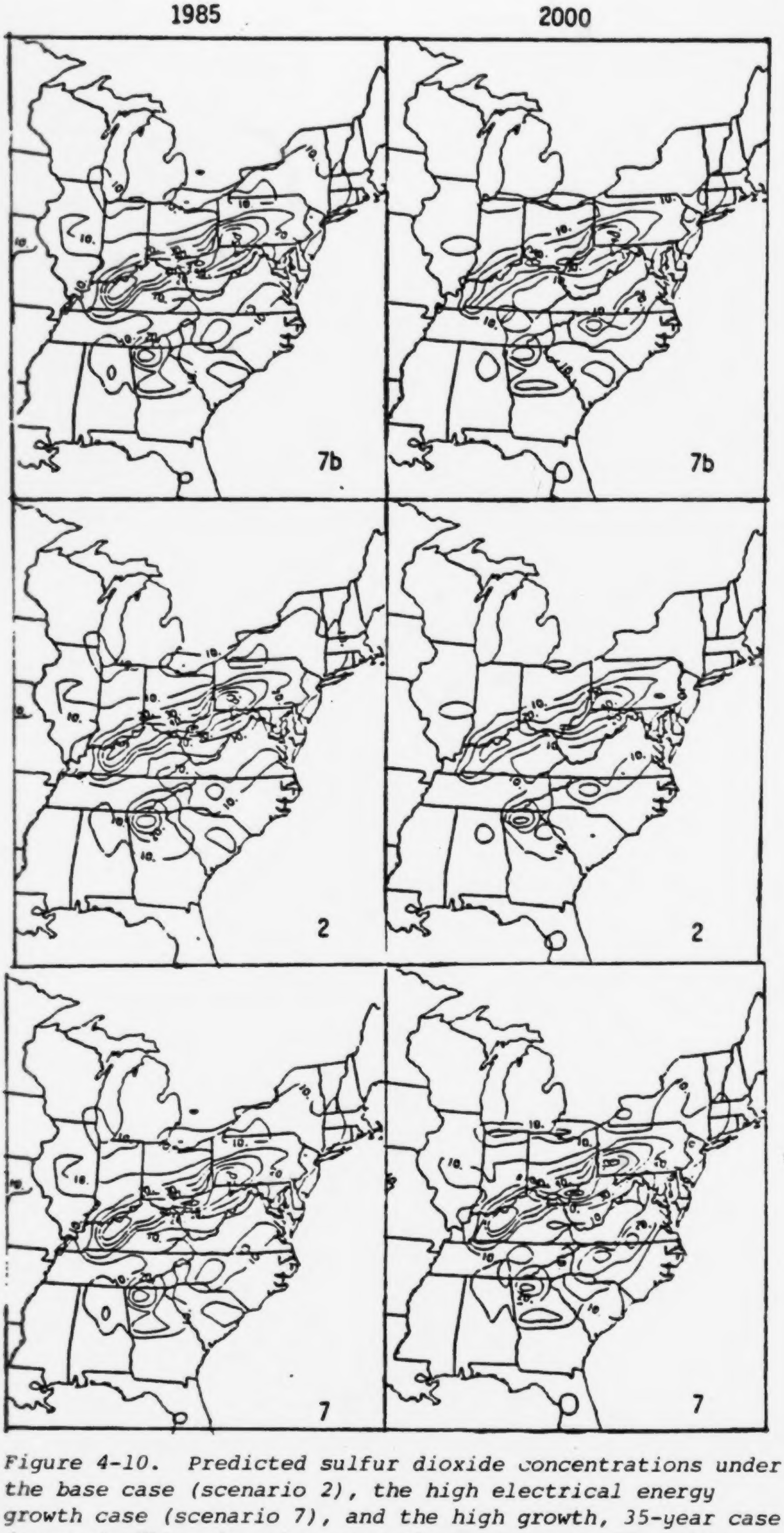


Figure 4-10. Predicted sulfur dioxide concentrations under the base case (scenario 2), the high electrical energy growth case (scenario 7), and the high growth, 35-year case (scenario 7b) using the meteorology of August 27, 1974.

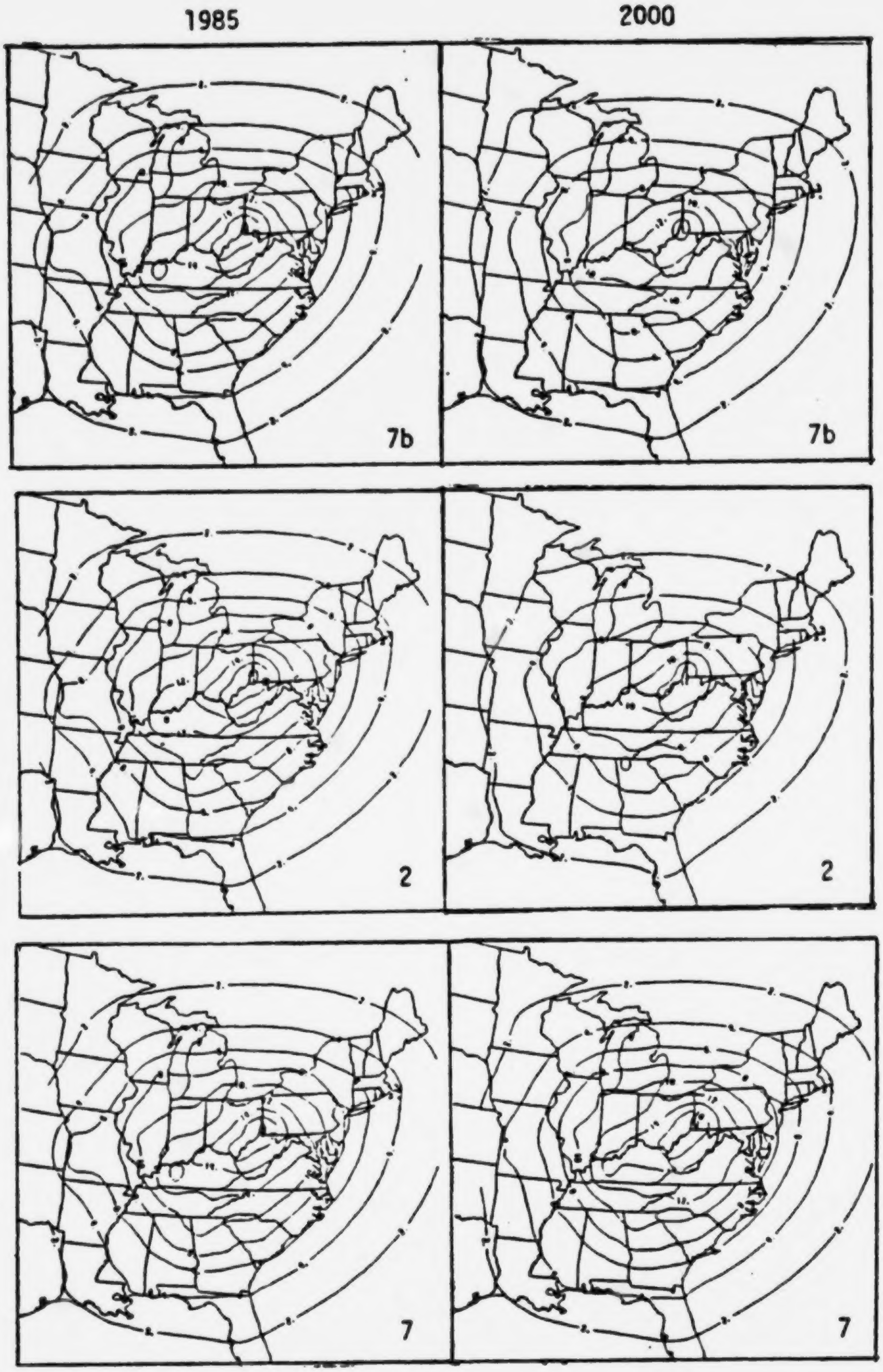


Figure 4-12. Predicted annual average sulfur dioxide concentrations under the base case (scenario 2), the high electrical energy growth case (scenario 7), and the high growth, 35-year case (scenario 7b).

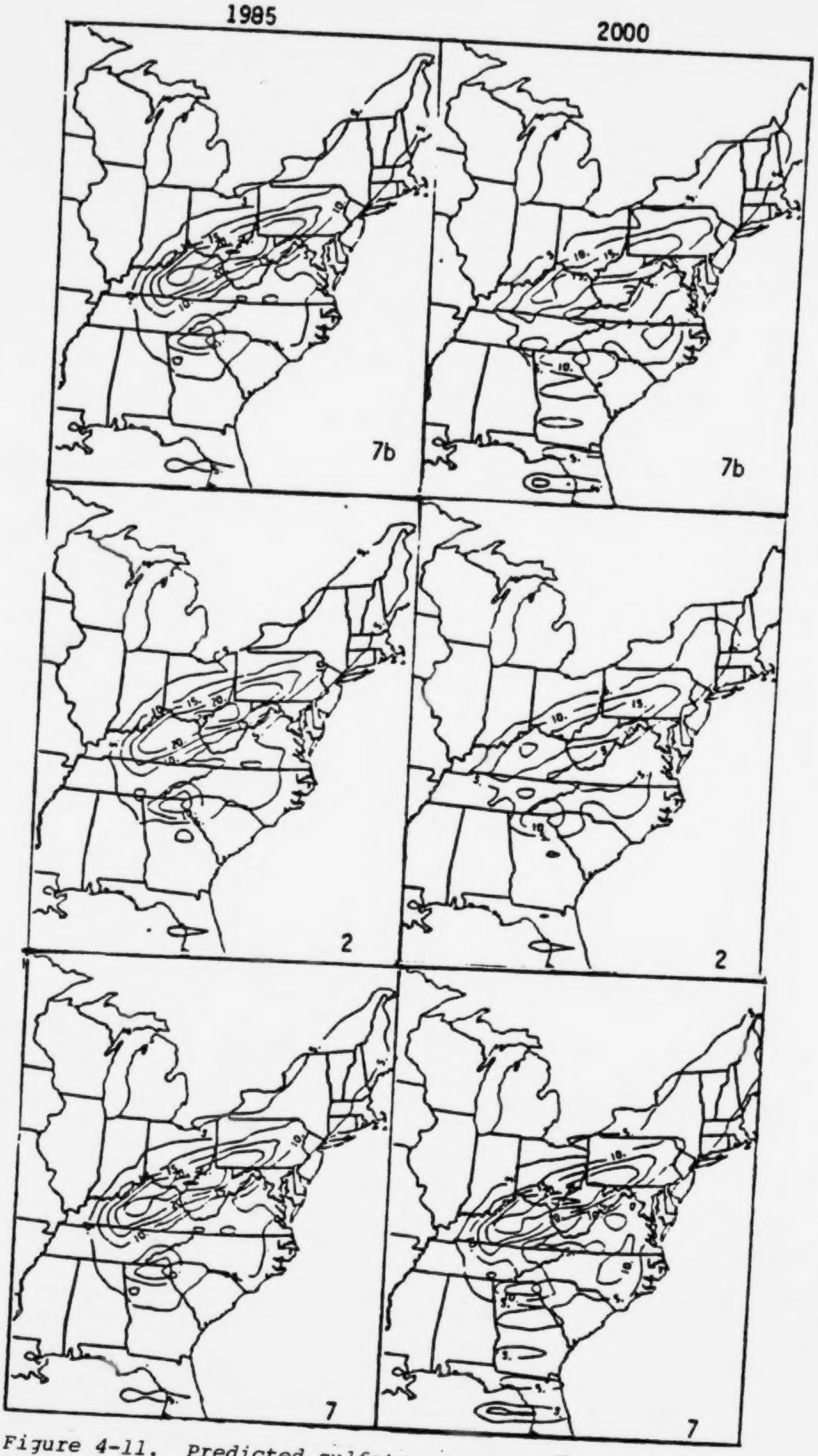


Figure 4-11. Predicted sulfate concentrations under the base case (scenario 2), the high electrical energy growth case (scenario 7), and the high growth, 35-year case (scenario 7b) using the meteorology of August 27, 1974.

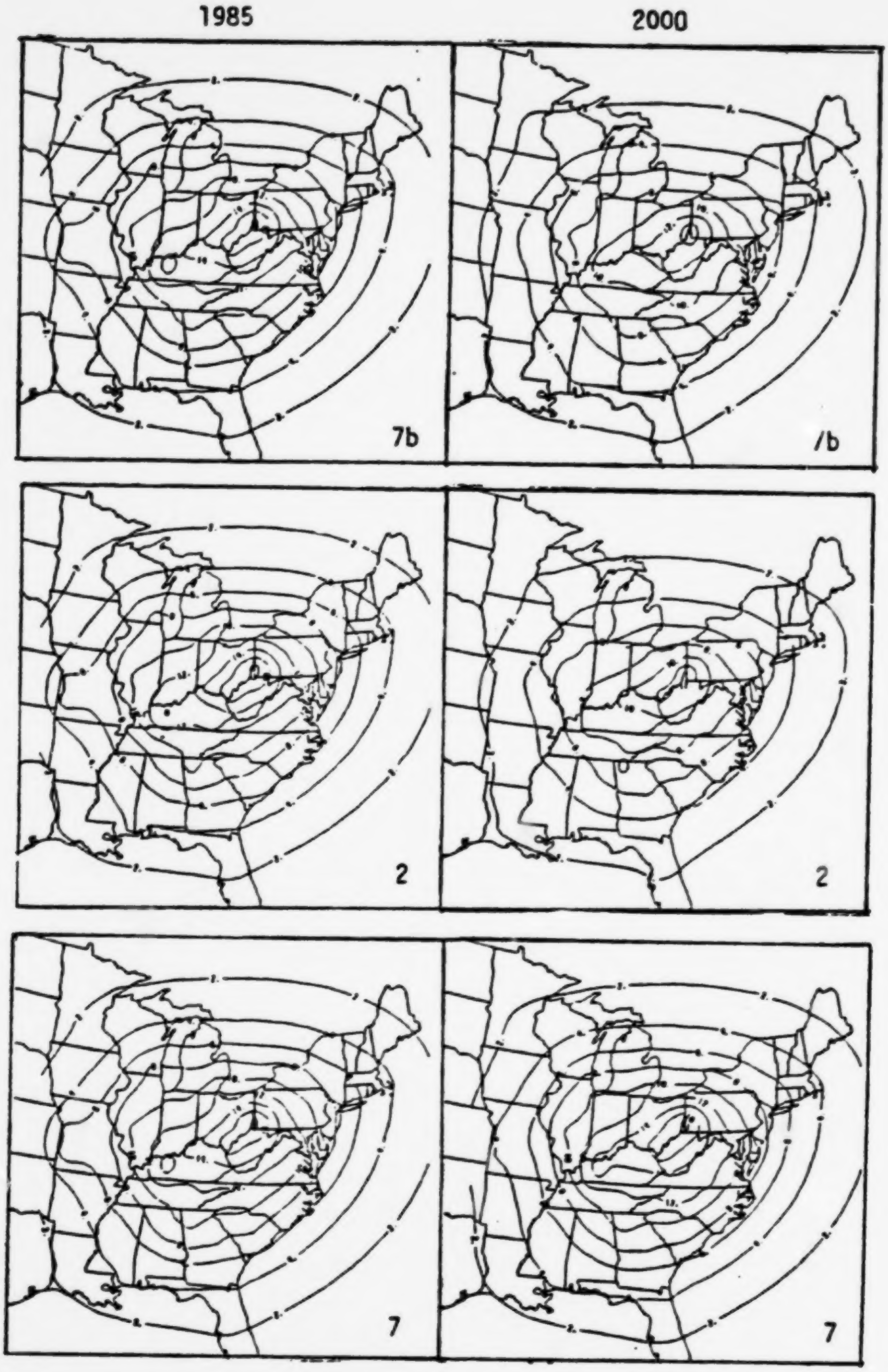


Figure 4-12. Predicted annual average sulfur dioxide concentrations under the base case (scenario 2), the high electrical energy growth case (scenario 7), and the high growth, 35-year case (scenario 7b).

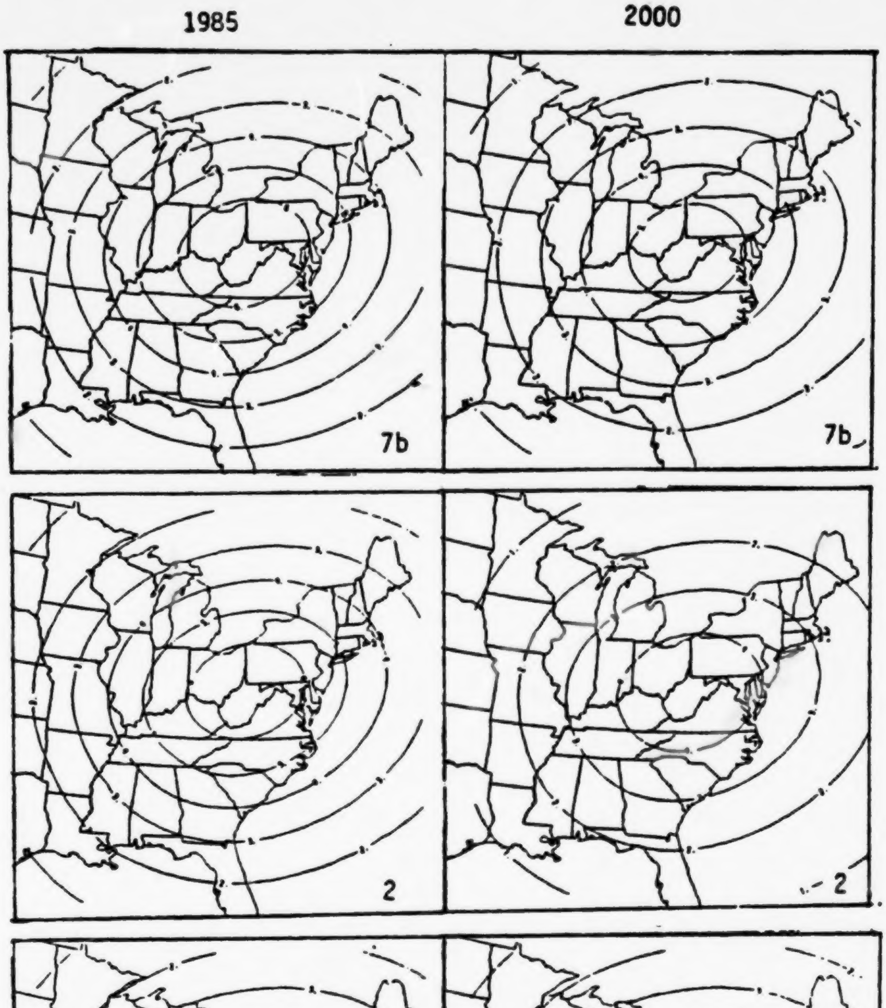


Figure 4-13. Predicted annual average sulfate concentrations under the base case (scenario 2), the high electrical energy growth case (scenario 7) and the high growth, 35-year case (scenario 7b).

concentration--almost the entire ORBES region--would be almost identical under both scenarios; the concentration levels, however, would increase under the high growth case.

4.4.2 High Electrical Energy Growth Variations (scenarios 7b and 7a)

4.4.2.1 High Growth, 35-year (scenario 7b) versus Base Case (scenario 2)

The high growth, 35-year case (scenario 7b) would result in nearly the same emissions and concentrations as those that are projected when a historic rate of growth in the demand for electricity is assumed (the base case).

- In 1985, utility sulfur dioxide, particulate, and nitrogen oxide emissions under the high growth, 35-year case would be almost identical to the emissions under the base case (see tables 4-1, 4-2, 4-3, and 4-4).

- In 2000, however, utility sulfur dioxide, particulate, and nitrogen oxide emissions under the 35-year case would be 8.3, 10.5 and 23 percent higher, respectively, than those of the base case in that year (see tables 4-2, 4-3, and 4-4).

In terms of plant types, sulfur dioxide emissions from SIP-regulated plants would be similar in 2000 under both the high growth, 35-year case and the base case. This similarity would occur because the additional installed capacity under the former case is subject to revised new source performance standards (RNSPS), which are the strictest of all the standards. (RNSPS units would provide about 67 percent of all coal-fired electrical generation in 2000 under the 35-year case.) Nevertheless, since each SIP unit emits five to six times more sulfur dioxide than a comparable RNSPS unit does, SIP emissions still would comprise the bulk of total emissions under the high growth, 35-year case, accounting for 2.9 million tons in 2000, or 62 percent of the 4.71 million tons emitted in that year.

Because utility sulfur dioxide emissions would be about the same in 1985 under both scenarios, utility-related annual and episodic sulfur dioxide and sulfate concentrations also would be about the same. In 2000, however, since emissions under the high growth, 35-year case would increase more between 1985 and 2000, utility-related annual and episodic concentrations would be somewhat higher under the high growth, 35-year case than under the base case.

- Episodic sulfur dioxide and sulfate concentrations related to utility emissions would be 8 percent and 4.5 percent higher, respectively, under the high growth, 35-year case than they would be in the area of highest episodic concentrations under the base case (see figures 4-10 and 4-11).

- Annual utility-related sulfur dioxide and sulfate concentrations would be 13 percent and 18 percent higher, respectively, under the 35-year case in 2000 than they would be in the area of highest annual concentrations under the base case (see figures 4-12 and 4-13).

4.4.2.2 High Growth, 35-year (scenario 7b) versus High Growth, 45-year (scenario 7)

One suggestion for achieving further emission reductions has concerned the reclassification of modified units. An estimate of the emission reductions possible under such a change can be made by comparing the emissions of the two high electrical energy growth cases--one with 35-year units and one with 45-year units.

- Under both the 45-year plant lifetime case and the 35-year plant lifetime case, sulfur dioxide emissions from all generating units (SIP, NSPS, and RNSPS units) as well as those from SIP regulated units alone would be the same in 1985.

- In 2000, sulfur dioxide emissions from SIP-regulated units would total 4.32 million tons under the 45-year plant lifetime case (see table 4-1); this amount is 49 percent higher than the 2.9 million tons emitted under the 35-year plant lifetime case.

- Sulfur dioxide emissions from all generating units (SIP, NSPS, and RNSPS) would total 6.06 million tons in 2000 under the 45-year plant lifetime case, or 29 percent higher than the 4.71 million tons emitted under the 35-year plant lifetime case (see table 4-2).

- Utility particulate and nitrogen oxide emissions would be about the same in 1985 under both the 45-year plant lifetime case and the 35-year plant lifetime case (see tables 4-3 and 4-4).

- By 2000, under the 45-year case, utility particulate emissions would be about 24 percent higher than the emissions under the 35-year case, and utility nitrogen oxide emissions would be about 7 percent higher than under the 35-year case.

Early retirement also would result in significantly reduced utility-related sulfur dioxide and sulfate concentrations in the year 2000.

- In the area that would experience the highest sulfur dioxide concentrations under the 45-year case, episodic sulfur dioxide concentrations would be 21 percent lower and episodic sulfate concentrations would be 37 percent lower in the year 2000 (see figures 4-10 and 4-11).

- Annual sulfur dioxide and sulfate concentrations under the 35-year case in 2000 in the same area would be 42 percent and 31 percent lower, respectively, than those under the 45-year case (see figures 4-12 and 4-13).

4.4.2.3 Least Cost Dispatching (scenario 7) Versus Least Emissions Dispatching (scenario 7a)

However there are ways to reduce sulfur dioxide emissions under high electrical energy growth while retaining the feature of longer plant lifetimes. For example, units with 45-year lifetimes could be dispatched according to the least amount of sulfur dioxide emissions (scenario 7a) rather than according to least cost (scenario 7). If such a dispatching order was implemented, utility sulfur dioxide, particulate, and nitrogen oxide emissions and utility-related regional sulfur dioxide and sulfate concentrations would be lower than under least cost dispatch.

In general, utility sulfur dioxide emissions in the ORBES region would be significantly lower in 1985 and substantially lower in 2000 under the least emissions dispatch case than they would be under the least cost dispatch case.

- Sulfur dioxide emissions from SIP-regulated generating units in the ORBES region would be 24 percent and 65.3 percent lower in 1985 and 2000, respectively, under least emissions dispatch than they would be under least cost dispatch in the same years (see table 4-1).

- Sulfur dioxide emissions from all generating units (SIP, NSPS, and RNSPS) in the ORBES region would be about 21 percent and 45 percent lower in 1985 and 2000, respectively, under least emissions dispatch than they would be under least cost dispatch in the same years (see table 4-2).

- Utility particulate emissions would be about the same in 1985 under both assumptions (only 4 percent lower under least emissions dispatch). In 2000, however, utility particulate emissions would be significantly lower (19.2 percent) under the least emissions dispatch case than under the least cost dispatch case. See table 4-3.

- Nitrogen oxide emissions would be 5 percent lower in 1985 and 8.4 percent lower in 2000 under the least emissions dispatch case than they would be under the least cost dispatch case (see table 4-4).

The reason for this difference involves the assumption of nitrogen oxide standards for NSPS and RNSPS units in contrast to the absence of such standards for SIP units. Since NSPS and RNSPS units would be in service more of the time under least emissions dispatching, the least emissions dispatch case would lead to slightly lower nitrogen oxide emissions than the least cost dispatch case, in which SIP units are in service more of the time.

- Episodic concentrations in the area that experienced the highest concentrations in the year 2000 under the least cost case would be lower under least emissions dispatching: episodic sulfur dioxide concentrations would be 51 percent lower, and episodic sulfate concentrations, 36 percent lower. See figures 4-14 and 4-15.

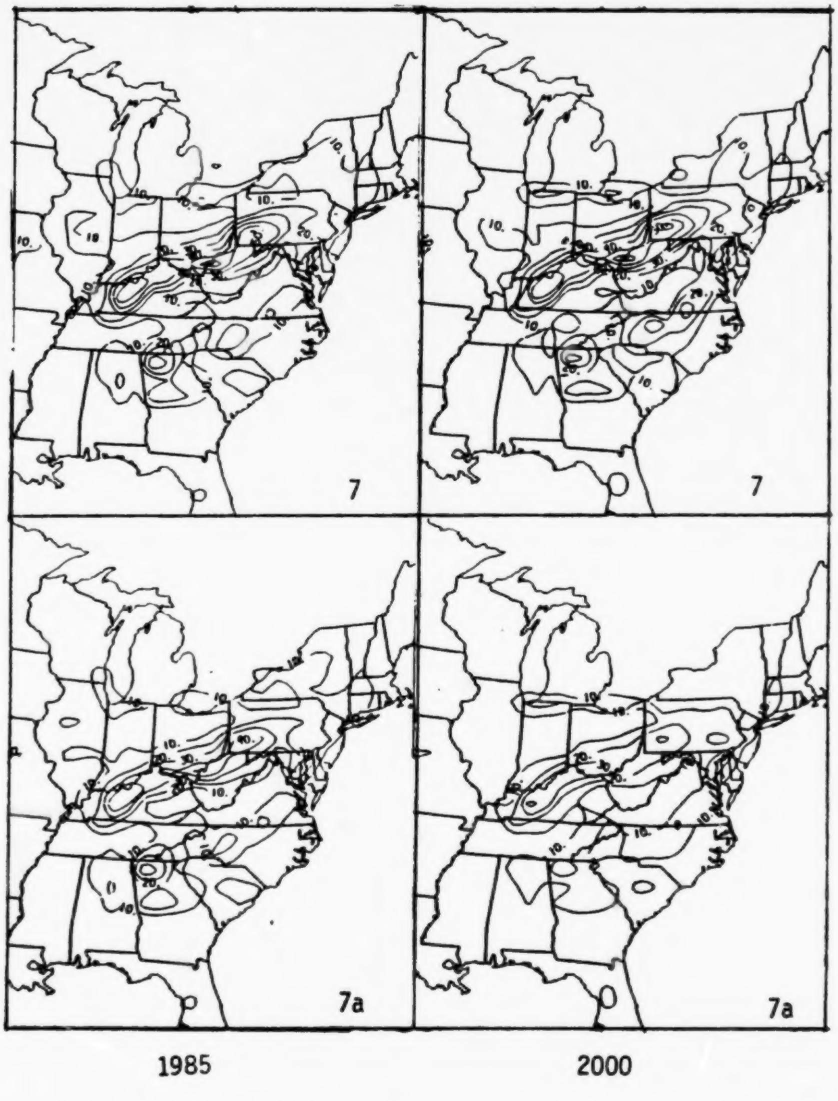


Figure 4-14. Predicted sulfur dioxide concentrations under the least cost dispatching case (scenario 7) and the least emissions dispatching case (scenario 7a) in 1985 and 2000 using the meteorology of August 27, 1974

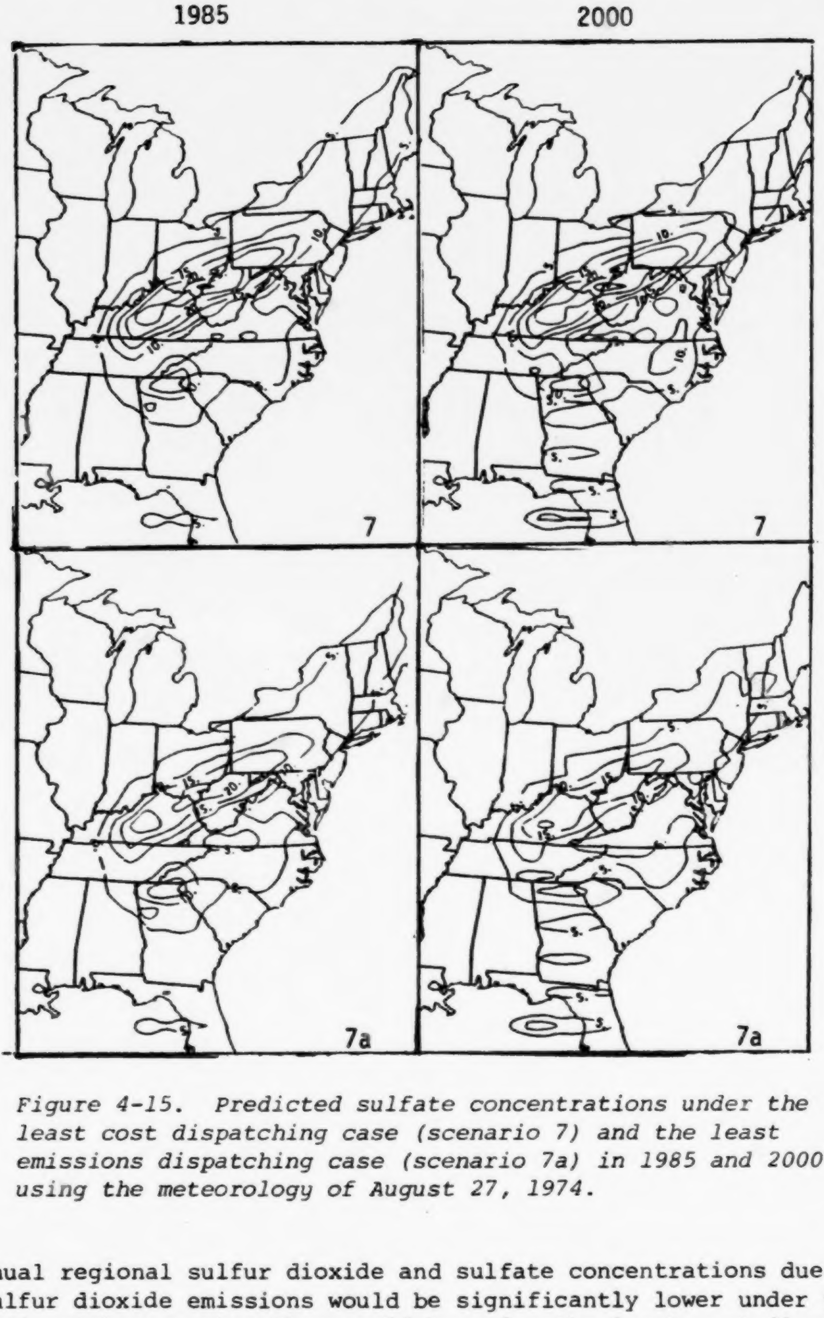


Figure 4-15. Predicted sulfate concentrations under the least cost dispatching case (scenario 7) and the least emissions dispatching case (scenario 7a) in 1985 and 2000 using the meteorology of August 27, 1974.

Annual regional sulfur dioxide and sulfate concentrations due to utility sulfur dioxide emissions would be significantly lower under the least emissions dispatch case than they would be under the least cost dispatch case. See figures 4-16 and 4-17.

- In 1985, in the area of highest concentrations, annual regional sulfur dioxide and sulfate concentrations due to utility sulfur dioxide emissions would be about 12 percent lower under least emissions dispatch than the concentrations projected under least cost dispatch.

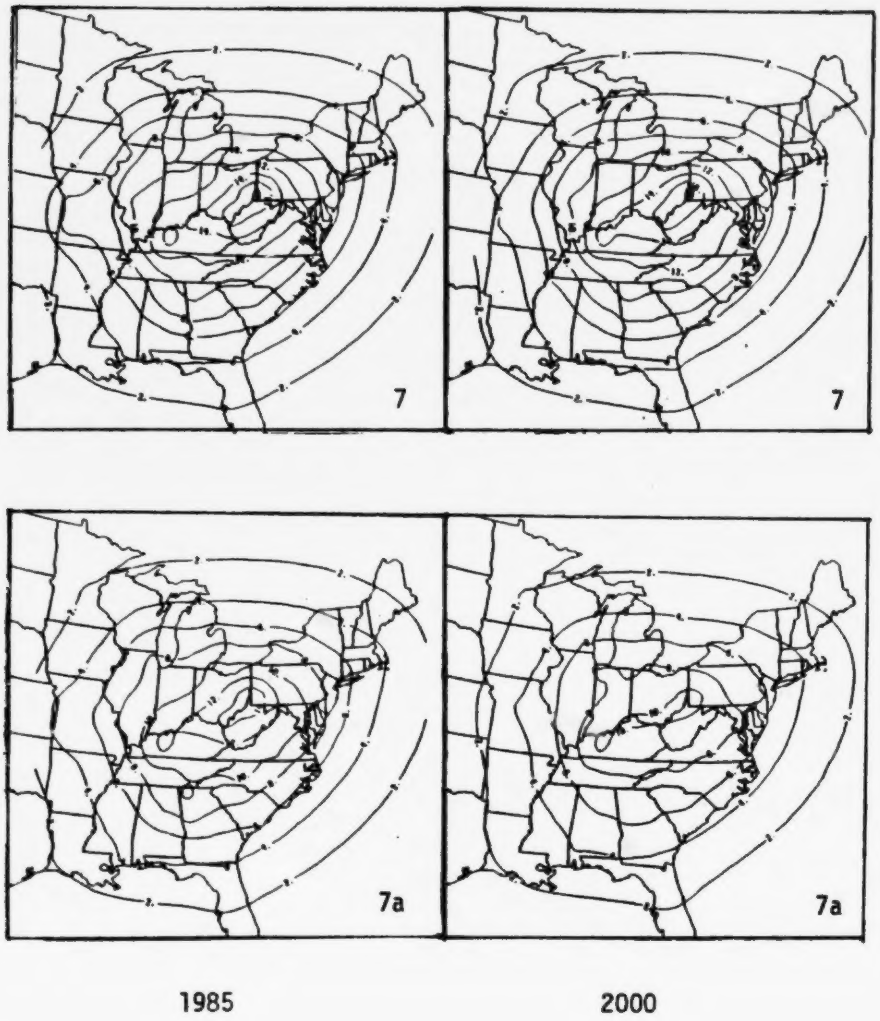


Figure 4-16. Predicted annual average sulfur dioxide concentrations under the least cost dispatching case (scenario 7) and the least emissions dispatching case (scenario 7a) in 1985 and 2000.

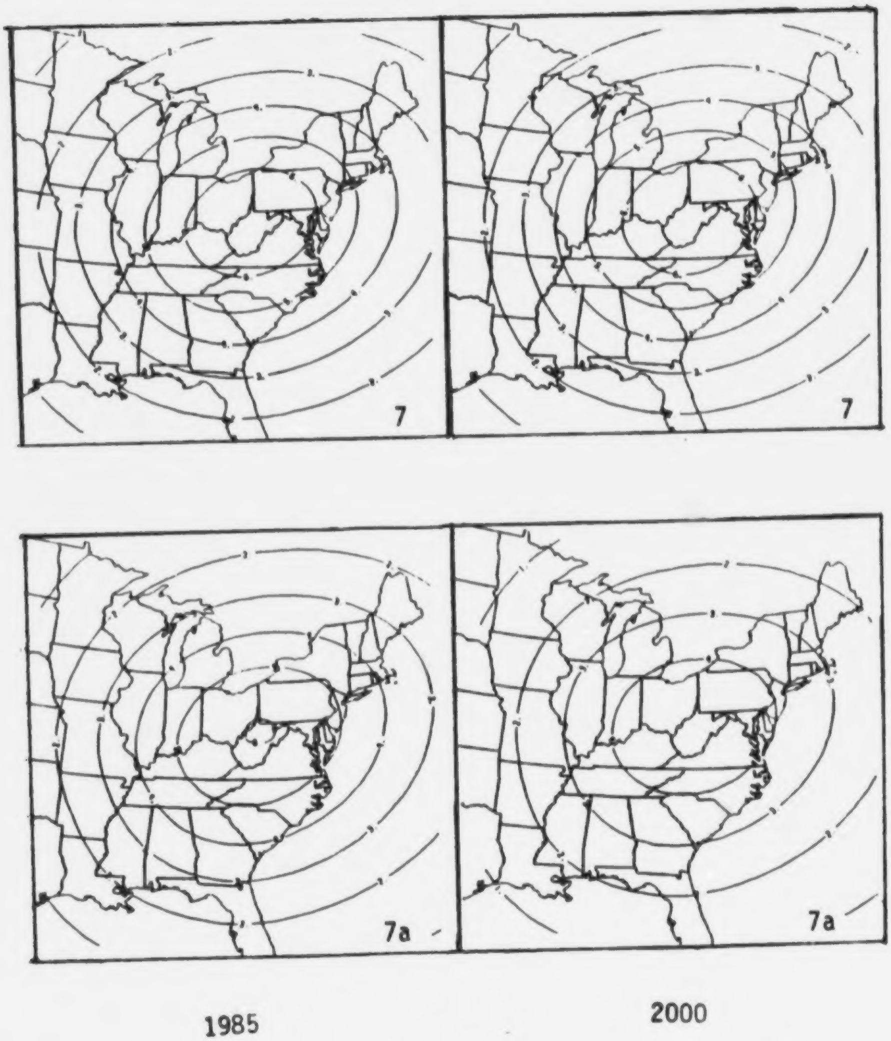


Figure 4-17. Predicted annual average sulfate concentrations under the least cost dispatching case (scenario 7) and the least emissions dispatching case (scenario 7a) in 1985 and 2000.

- In 2000, annual regional sulfur dioxide and sulfate concentrations due to utility sulfur dioxide emissions would be about 42 and 31 percent lower, respectively, under least emissions dispatch than the concentrations projected under least cost dispatch.

4.5 Electrical Exports (scenario 2a)

Because more coal-fired units would be sited in the ORBES region between 1985 and 2000 under the electrical exports case (scenario 2a) than under the base case (scenario 2), regional utility sulfur dioxide, particulate, and nitrogen oxide emissions would be higher in 2000 under the exports case than they would be under the base case. However, the increase would be small because it is assumed that all exported power will be supplied by units governed by the revised new source performance standards (RNSPS), which are the strictest of the three standards (state implementation plans (SIPs), new source performance standards (NSPS), and RNSPS).

- In the year 2000, utility sulfur dioxide emissions from all generating units in the ORBES region would be only 4.6 percent higher under the exports case than under the base case, and utility particulate emissions would be about 5.3 percent higher under the former case than under the latter in that year. Finally, utility nitrogen oxide emissions in 2000 would be about 11 percent higher under the exports case than under the base case. See table 4-5.

4.6 Fuel Substitution and Conservation Emphasis Scenario

4.6.1 Natural Gas Substitution (scenario 4)

An emphasis on the use of natural gas for commercial and residential space heating in the ORBES region (scenario 4) would result in a lower demand for electricity than under base case (scenario 2), and thus fewer emissions from electrical generating units. As a result, episodic concentrations would be lower under the natural gas case than under the base case. Annual concentrations, however, would be expected to be nearly the same under both scnenarios.

- Under the natural gas substitution case, sulfur dioxide emissions from SIP-regulated units would be 2 percent lower in 1985 than under the base case in that year. However, sulfur dioxide emissions from SIP-regulated units would be slightly higher than under the base case in 2000 (4 percent). An increased use of existing facilities under a natural gas substitution is responsible for this slight increase by 2000 (see table 4-1).

Table 4-5. Sulfur Dioxide, Particulate, and Nitrogen Oxide Emissions, ORBES Region, Electrical Exports Case (Scenario 2a), Nuclear Fuel Substitution Case (Scenario 2c), and Conservation Emphasis Case (Scenario 6), Year 2000

	Sulfur Oxide Emissions	Particulate Emissions	Nitrogen Oxide Emissions
		(millions of tons)	
1976	8.94	1.38	1.49
Base Case	4.35	0.19	2.00
Electrical Exports	4.55	0.20	2.22
Nuclear Fuel Substitution	4.21	0.18	1.84
Conservation Emphasis	3.87	0.16	1.47

Under the natural gas substitution case, sulfur dioxide emissions from all generating units--SIP, NSPS, and RNSPS units--would decrease 4 percent by 1985 and 10 percent by 2000 from base case emission levels for all units in those years (see table 4-2).

Under the natural gas emphasis case, utility particulate emissions in the ORBES region would be 16 percent lower by 1985 and 21 percent lower by 2000 than the base case emission levels in those years (see table 4-3).

Under the natural gas substitution case, utility nitrogen oxide emissions in the ORBES region would be 12 percent lower by 1985 and 16 percent lower by 2000 than the base case emission levels in those years (see table 4-4).

Under the natural gas substitution case, episodic sulfur dioxide and sulfate concentrations would be 25 and 15.6 percent lower, respectively, in the year 2000 than they would be under the base case in that year (see figures 4-18 and 4-19).

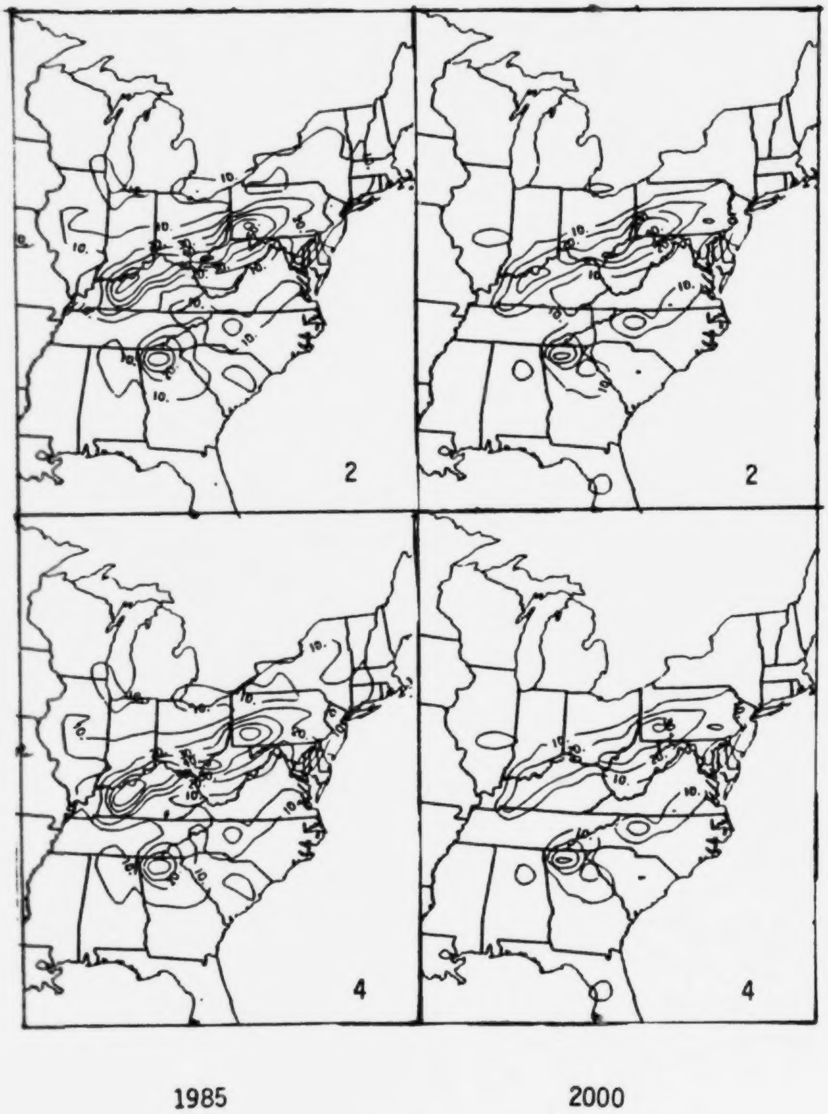


Figure 4-18. Predicted sulfur dioxide concentrations under the base case (scenario 2) and the natural gas substitution case (scenario 4) using the meteorology of August 27, 1974.

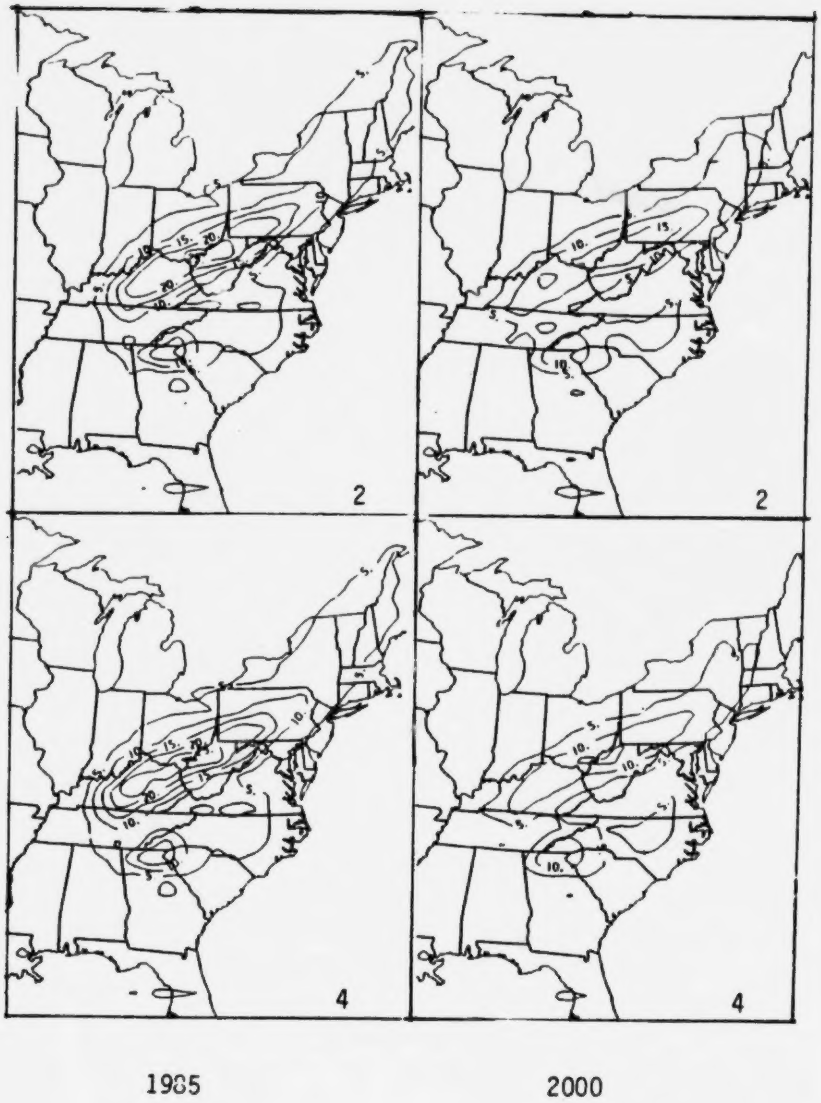


Figure 4-19. Predicted sulfate concentrations under the base case (scenario 2) and the natural gas substitution case (scenario 4) using the meteorology of August 27, 1974.

Annual average concentrations also would be lower under the natural gas case, although not as dramatically. Figures 4-20 and 4-21 compare the annual average sulfur dioxide and sulfate concentrations under the base case and the natural gas case. As can be seen, the area affected by concentrations of a given magnitude would be slightly smaller under the latter case than under the former.

- In general, annual average concentrations would be about 7 percent lower under the natural gas case in the year 2000 than under the base case in that year.

4.6.2 Nuclear Fuel Substitution (scenario 2c) and Conservation Emphasis (scenario 6)

Only emission calculations were performed for the nuclear fuel substitution case (scenario 2c) and the conservation emphasis case (scenario 6), and then only for the year 2000. (No air quality calculations were performed for the alternative fuel substitution case--scenario 3.)

- The conservation emphasis case would result in utility sulfur dioxide emissions 11 percent lower in 2000 than those under the base case in that year (see table 4-5).

- The nuclear fuel substitution case would result in utility sulfur dioxide emissions only 3 percent lower in 2000 than those under the base case in that year (see table 4-5).

The expanded use of generating units governed by state implementation plans (SIPs) explains why these fuel substitution and conservation scenarios would result in utility sulfur dioxide emissions quite similar to those of the base case. Under the conservation emphasis case fewer new generating units (75 fewer units) would be built than under the base case; under the nuclear substitution case, half of the new units added after 1985 would be nuclear fueled rather than coal fired. As a result, SIP-regulated generating units would be used more than they would under the base case, where some of the electrical generation would shift to new, cleaner units governed by revised new source performance standards (RNSPS).

- Utility particulate emissions would be about 26 percent lower in the year 2000 under the conservation emphasis case than under the base case in that year (see table 4-5).

- The nuclear fuel substitution case would result in utility particulate emissions about 8 percent lower in 2000 than those under the base case in that year (see table 4-5).

Unlike the coal-dominated scenarios, these fuel substitution and conservation scenarios would not raise utility nitrogen oxide emissions at all

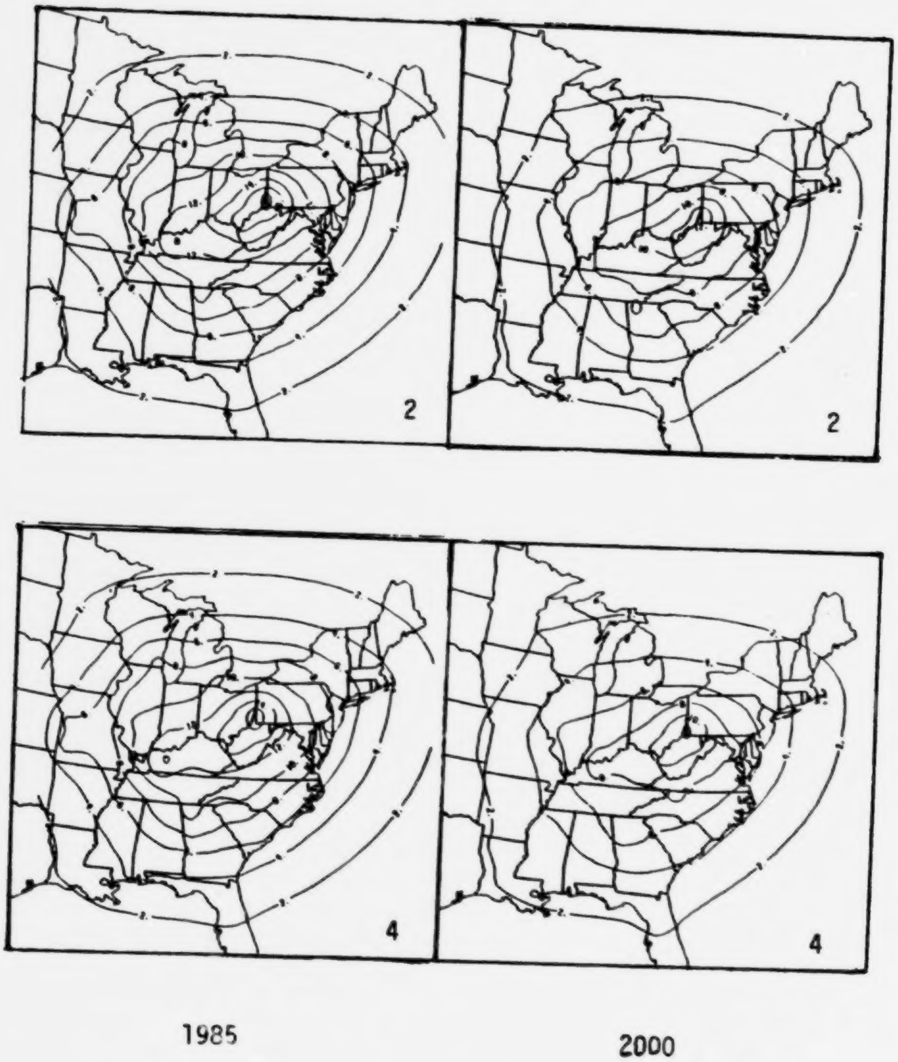


Figure 4-20. Predicted annual average sulfur dioxide concentrations under the base case (scenario 2) and the natural gas substitution case (scenario 4).

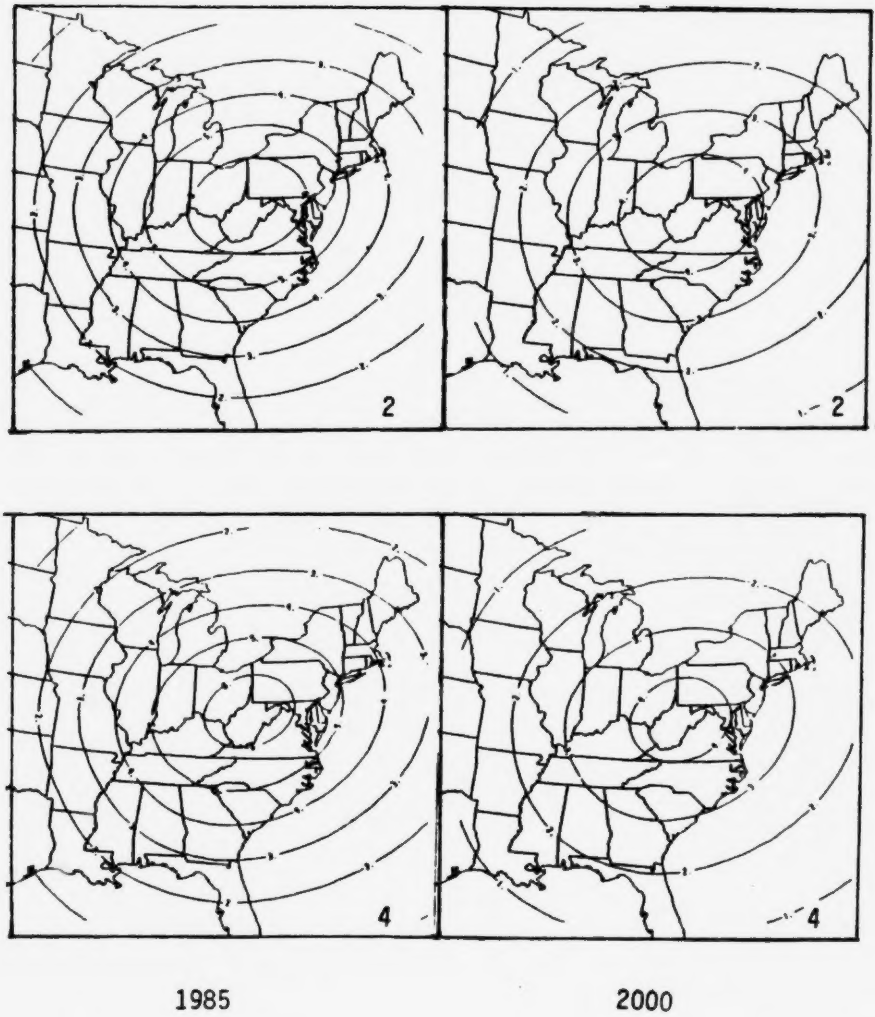


Figure 4-21. Predicted annual average sulfate concentrations under the base case (scenario 2) and the natural gas substitution case (scenario 4).

or as much (see table 4-5). Such emissions rise in proportion to increased generating capacity, and less capacity is installed under the nuclear fuel substitution case and the conservation emphasis case than under the base case.

- In fact, under the conservation emphasis case, utility nitrogen oxide emissions would be lower in the year 2000 than in 1976. In contrast, the strict environmental control case would result in the lowest utility nitrogen oxide emissions in 2000 of all of the coal-dominated cases, and it still would increase utility nitrogen oxide emissions about 34 percent over the 1976 levels.

- The nuclear substitution case would raise utility nitrogen oxide emissions significantly (about 23 percent) from the 1976 levels. Even this increase, however, would result in lower emission levels than any of those projected for the coal-dominated scenarios.

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